EVALUATION OF SUBSURFACE DRAINAGE TECHNIQUES USED FOR DRYLAND SALINITY CONTROL

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DATA ACKNOWLEDGEMENTS AND RESTRICTIONS

All raw data used in this study dated prior to 1997 were collected by the staff at Agriculture and Agri-Food Canada's Semiarid Prairie Agricultural Research Centre (SPARC) in Swift Current, Saskatchewan. Laboratory analyses were also completed by SPARC staff. These data and the information derived from these data are proprietary and are protected under copyright by Agriculture and Agri-Food Canada. All data collected from 1997 through 1999 were collected jointly by Agriculture and Agri-Food Canada and the University of Saskatchewan under a collaborative agreement funded through Agriculture and Agri-Food Canada. All raw data (all years) were analyzed by the author under the supervision of C. Maule (University of Saskatchewan). Please contact the Director (Semiarid Prairie Agricultural Research Centre, P.O. Box 1030, Swift Current, Saskatchewan, S9H 3X2) for permission to use any information resulting from the Agriculture and Agri-Food data used in this thesis.

ABSTRACT

Dryland soil salinity is a major problem throughout much of the northern Great Plains region. One method of controlling dryland salinity is through the use of subsurface drainage systems. However, in western Canada there is a general lack of experience in designing drainage systems. Usually those systems that are installed in semiarid dryland areas are based on experiences from more humid or irrigated areas.

This study evaluates two types of subsurface drainage systems installed in adjacent, similar saline seeps located near Swift Current, Saskatchewan. The two types of drainage systems evaluated are: (1) a traditional grid drainage design, typical of humid or irrigated regions and; (2) an experimental drainage design that uses a relatively smaller amount of tubing that is precisely placed and is valve controllable, allowing for the implementation of a water management plan. The two systems were evaluated based on their ability to control water tables, lower soil salinity, and provide the highest water quality possible so that the environmental impacts associated with re-using or discharging that water are minimized. Climatic, hydrologic, geologic and chemical data were used to characterize each saline parcel and then monitor hydrologic changes caused by the drainage systems.

From the results presented in this study, there was evidence that, with modifications to the water management plan, the experimental system would be equally effective at lowering water tables as the traditional system. The study was inconclusive as to which drainage technology had the better ability to reduce soil salinity above the drain lines. Also, the salinity of the experimental drainage system effluent was observed to be much lower than that of the traditional system.

Overall, both systems performed as they were designed indicating that both technologies can be successfully used in a dryland situation. However, in consideration of the reduced cost and installation effort and the more flexible operation options of the experimental system, the experimental design concept is perhaps better suited to modern agriculture on the semiarid prairies. Recommendations for use of this technology include adaptations to the water management plan that would further minimize salinization hazards.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

dS – decisiemen

EC – electrical conductivity

EC_e – electrical conductivity of saturate paste extract

meq – milliequivalent

r^2 – coefficient of determination

SAR – sodium adsorption ratio

α - level of significance

1. INTRODUCTION

1.1 Background

Throughout the Great Plains region of North America, human activities have aggravated naturally favourable conditions for dryland saline seep development. Saline seeps are recently developed saline soils that are wet some or all of the time, often with white salt crusts, where vegetation production is reduced or eliminated (Miller et al. 1981). The problem is attributed to temporary excesses of surface and groundwater (Sommerfeldt and MacKay 1982) caused by recent human activities and natural geologic conditions. The practice of summer-fallowing, development that interferes with natural drainage courses, and natural variations in surface and subsurface geology all contribute to the occurrence of saline seeps. Researchers at Agriculture and Agri-food Canada's Semiarid Prairie Agricultural Research Centre (SPARC) at Swift Current, Saskatchewan, have shown that the installation of subsurface drainage combined with plantings of tall wheatgrass (*Thinopyrum ponticum)* barriers have effectively lowered water tables, reduced soil salinity, and increased barley yields within a seep area (Steppuhn and Wall 1997).

Due to the low economic worth of most agricultural crops, and the relatively small size of most saline seeps, the cost of an intense subsurface investigation followed by the cost of having a drainage system professionally installed with specialized equipment is prohibitive for a large number of farmers. Due to the low demand for subsurface drainage within the prairies, there is a general shortage of experience in remediating dryland seeps. The majority of the drainage projects have been designed using criteria derived from humid regions. Criteria derived from these regions can be successfully transferred to irrigated areas but usually fails when transferred to dryland areas where a lack of leaching water prevents rapid reclamation of the soil (Paterson and Jensen 1984). In the prairies, recent research efforts have concentrated on using biological controls in the recharge areas that supply water to the seeps. This usually means planting deep-rooted vegetation with high moisture requirements in recharge areas to prevent water escaping the root zone and moving to groundwater tables. However, in many cases the recharge area supplying a saline seep on a particular piece of land is not owned by the same farmer so more aggressive approaches must be taken. In an effort to make subsurface drainage more attractive to farmers, SPARC researchers teamed up with farmers near Swift Current, university professors, government extension agencies, and drainage engineers to decide what modifications to present subsurface drainage technology would have to be made to customize it to western dryland agriculture. It was decided that a professionally installed grid drainage system based on humid experience is likely excessive for the much drier prairies. As well, there is not always an adequate option for disposal of drainage effluent as a permit is generally required before any water can be discharged across the landowner's legal boundaries.

A major problem with using subsurface drainage for salinity control is that salts are often transported from an area of high concentration to another point, essentially just moving the problem to another area. This is clearly not consistent with the goals of sustainable agriculture. Under irrigation, subsurface drainage has been shown to effectively leach most of the salts from the soil profile within a relatively short time (Hogg and Tollefson 1992). Unless an ideal discharge option is available, clearly this is a rather limited solution when considered on a regional scale. However, the treatment of dryland salinity with subsurface drainage may offer unique opportunities to remain within the sustainable agriculture concept. Eilers (1995) suggests that "soil salinity is a water problem first and a soil problem second", meaning that controlling the hydraulic gradients within the site is the key to amelioration. The notion that water excesses are causing the problem is quite paradoxical considering the semiarid climates associated with dryland seeps, especially because most areas within a field experience moisture deficiencies for most or all of the growing season. A system of removing water from areas with super-abundant quantity and supplying areas with inadequate moisture reserves would benefit both areas and present a synergistic hydrologic system and hence the concept of water harvesting is introduced.

Researchers had the opportunity to compare a traditional grid drainage system to an experimental prototype system at a site near Swift Current. The study field has two similar saline seeps located adjacent to one another in a mid-slope position. The southernmost seep was fitted with traditional grid drainage installed by a professional drainage contractor in 1991 as part of a study to evaluate the effectiveness of this technology in western Canada. In the fall of 1997, a new experimental drainage system was installed in the northern seep. The purpose of the latter was to act as a collector for a water harvesting system that would supply water for down-slope irrigation of field shelterbelts. The design objectives for the experimental drainage system were as follows: (1) to be equally as effective at lowering the water table as the commercial system thereby reducing the soil salinization potential; (2) to test two depths that both require a much smaller installation effort than the commercial installation; (3) to provide a usable quantity of water that is of substantial quality and; (4) to require a relatively inexpensive and simple installation. Research data from the two sites has been collected since 1985, specifically monitoring piezometric levels, watertable levels, soil moisture, soil chemistry, water quality (from formation and from drain discharges), geology, and climatic information.

The study described in this thesis evaluates two different drainage concepts and recommends which is better-suited to western Canada. The overall goals of this work are: (1) to procure design criteria based on performance differences between the different drainage treatments and; (2) to infer into the adaptability of this technology so that it may be applied, with modifications, to any other terrain in the prairies based on a preliminary subsurface investigation.

1.2 Specific Objective

The primary objective of this thesis was to complete performance evaluations of each of the two drainage systems tested and make recommendations for the application of this technology to a semiarid prairie environment.

The definition of drainage performance within the context of this text is the ability to: (1) maintain hydraulic control by lowering the water table to the depth of the installed drains; (2) lower the total dissolved salt content of the soil solution above the drain lines; and (3) provide water that is of a suitable quality so that the environmental problems associated with discharging or using the water in a downstream area are minimized.

Note that the performance of a drainage system is not only a function of the technology itself, but also of the water management plan used by the landowner. To attain the research objective, each system will be evaluated in light of its original design objectives and the water management plan used. More detailed information about the specifications and design criteria used for each system can be found in Section 3.3.

In making recommendations as to the suitability of subsurface drainage for dryland salinity control, unique features of the two systems will be discussed in relation to the role they play in the systems performance. Ultimately, through comparison of the two drainage systems and water management plans, recommendations for the ideal technology and management plan that is suitable for use on the prairies will be made. This decision will be based exclusively on the previously described performance criteria.

2. LITERATURE REVIEW

2.1 Saline Seep Development

Salinity is the property of water that indicates the concentration of its dissolved constituents (Tanji 1990). All natural waters contain soluble solids and therefore possess a degree of salinity. When the water contained in the soil interstices embodies a higher concentration of dissolved ions than is present in the cells of plants, problems may occur. An ionic gradient can be established that prevents water and nutrients from reaching the plant, a toxicity problem can be created from an overabundance of a specific ion, or in some cases soil structure may deteriorate. Salinization refers to the processes contributing to the ionic enrichment of waters, commonly from the dissolution of sulfate, chloride and carbonate salts (Steppuhn 1992).

There are three components necessary for salinization to occur: (1) an influx of water into the soil that may or may not already possess a high degree of salinity; (2) the dissolution of salts into that water and; (3) a discharge of that same water to the atmosphere via evaporation that results in accumulation of salts within the root zone (Steppuhn et. al 1992; van der Kamp and van Stempvoort 1992). A situation where a contributing portion of any one of these three components is increased relative to the others will usually result in an increase in salinity.

Salinity generally only occurs in arid and semiarid regions (United States Salinity Laboratory Staff 1954). In humid climates the proportion of the evaporation component is small relative to precipitation, preventing the establishment of dominant upward gradients. The greatest hazard of salinization will occur in irrigated areas where the input of water into the system is increased and evaporative conditions remain high. That is not to say that salinity doesn't occur in non-irrigated areas. A 1992 estimate suggested that Alberta, Saskatchewan and Manitoba combined have 2.23 million ha of land that experience a 25% reduction in yield due to dryland salinity (Vander Pluym and Harron 1992). Often salinization problems occurring in dryland areas are referred to as saline seeps (Miller et al. 1981).

2.1.1 Types of saline seeps

Three factors required to create a salinity problem are groundwater recharge, mineral dissolution, and evaporation. Figure 2.1 represents a generalized saline seep. For identification and discussion of the various classifications of dryland saline seeps used in the Canadian prairies the reader is referred to Alberta Agriculture, Food and Rural Development (1997) and Halvorson (1990). Often saline seeps are more complex than these generalized cases and can actually be produced by a number of different mechanisms (Stein and Schwartz 1990). Seep types that deserve particular mention in the scope of this text are the contact seep (Alberta Agriculture, Food and Rural Development 1997) and texture change seep (Halvorson 1990).

A contact seep (Figure 2.2) is formed where groundwater flows through a permeable layer that overlies a less permeable layer until the permeable layer thins out (Alberta Agriculture, Food and Rural Development 1997). This causes a high water table to occur because of a reduction in the cross sectional area transverse to the direction of flow.

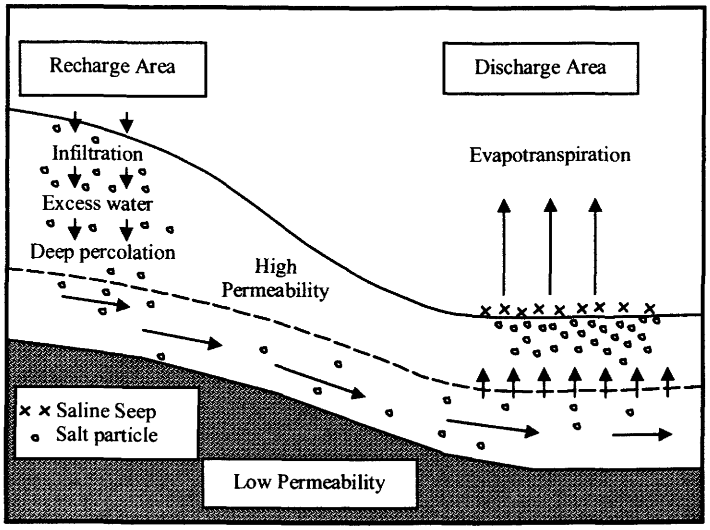


Figure 2.1: Generalized saline seep. (Adapted from Alberta Agriculture, Food and Rural Development (1997))

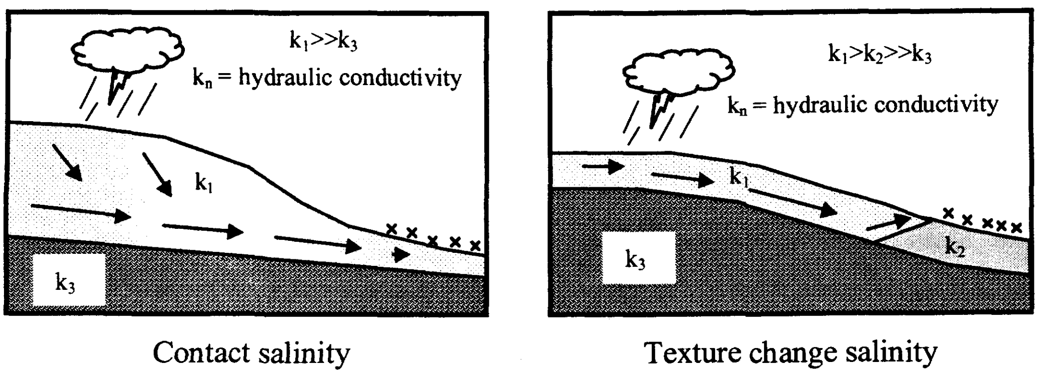


Figure 2.2: Common types of saline seeps. (Adapted from Alberta Agriculture, Food and Rural Development (1997) and Halvorson (1990))

A textural change seep (Figure 2.2) occurs where recharge water that flows through a relatively course material situated above an impermeable base encounters a reduction in texture (Halvorson 1990). A high water table ensues from an increase in the resistance of the flow-path causing subsurface water to collect at the point of the texture change.

2.1.2 Seep hydraulics

The source of water responsible for creating a saline seep can be quite variable. Many authors attribute the main cause of dryland salinity to the conversion of natural grasslands to cultivated lands (Steppuhn et al. 1992; Sommerfeldt and MacKay 1982; Miller et al 1981). In other cases, man-made development features such as road ditches, windbreaks, and other alterations to natural drainage courses can artificially augment recharge (Sommerfeldt and MacKay 1982; Hendry and Schwartz 1982; Stein and Schwartz 1990). Keller and Van der Kamp (1988) cite micro-topographic focussing of surface water as an important source of recharge in some relatively permeable tills found in Saskatchewan. They also suggest that a recharge rate of 10 mm/year may be sufficient to create a salinization problem in a case such as this. Similarly, Doering and Sandoval (1976) calculated recharge rates that varied from 1.8–47.4 mm/year in five years reported in a study located in southwestern North Dakota. In a study completed by Christie et al. (1985), soil moisture at a 1.2–6.0 m depth in cultivated fields increased by 10 mm/year and 4 mm/year for dark brown and brown soil zones respectively over that of adjacently located natural grassland.

With respect to salinity, climate is probably the most important factor to consider because it so strongly influences mineral precipitation reactions (Hendry and Schwartz 1982). Evaporation typically exceeds precipitation throughout the entire Great Plains region for most of the growing season. Consequently, salt laden water that is in close proximity to the soil surface will present a salinization hazard. Hillel (1980) suggests that as long as the suction head at the soil surface is greater than the depth of the water table there will be a tendency for water to be drawn towards the surface. However, the upward flux due to capillary action will vary according to soil texture, depth to water table and soil water gradient (van Hoorn and van Alphen 1994). Correspondingly, the depth at which a water table must be maintained to prevent salinization is largely dependent on soil texture. Stein and Schwartz (1990) observed the most severe salinity problems in locations where the water table is at a depth less than 1.5 m.

2.1.3 Seep chemistry

In the Western glaciated plains, most groundwater contains large quantities of inorganic salts (van der Kamp and van Stempvoort 1992). Sodium (Na^{+}), calcium (Ca^{2+}), and magnesium (Mg^{2+}) are the dominant cations and sulfate (SO_4^{2-}) is the dominant anion in most of the shallow groundwater systems associated with saline seeps (Halvorson 1990). It is currently believed that the main sulfur (S) source in the Glaciated Plains is oxidized pyrite found in the till and near surface shale units, although some oxidized organic S is also believed to contribute (Mermut et al. 1992; van der Kamp and van Stempvoort 1992).

2.1.4 Methods of controlling saline seeps

Any successful approach to controlling salinity must involve the negation of one or more of the conditions necessary for salinization. Steppuhn (1992) suggests three steps required for controlling root-zone salinity: (1) preventing the accumulation of water and salts within the root zone; (2) lowering groundwater tables and piezometric surfaces responsible for creating gradients necessary for salinization and; (3) removing salts from within the root zone.

The accumulation of water and salts within the root-zone can be prevented by reducing the recharge component or by reducing evaporative demand. In order to arrest or minimize the recharge component of a saline seep, a balance must be contrived between the amount of water added to the system, usually by precipitation or by seepage from water bodies, and that which is actually needed by plants. Selecting perennial plants that more aptly befit the natural hydrologic system and reducing the practice of summer-fallowing are common strategies suggested for this purpose (Eilers et al. 1995; Steppuhn et al. 1992; Halvorson 1990; Miller et al. 1981). A suggested method of reduction of evapotranspirative forces in the salinized area is the use of surface mulch or the establishment of windbreaks (Steppuhn 1992; Halvorson 1984).

Lowering groundwater potentials can greatly reduce salinization rates if the resulting groundwater gradients are small or directed away from the soil surface in the discharge area. One way that this can be accomplished is by using deep-rooted vegetation such as alfalfa (Eilers et al. 1995; Halvorson 1990) that can root to depths of 4–6 m (Miller et al. 1981) to lower the water table in up-slope and mid-slope positions. Drainage of surface water bodies has also been a suggested method to reduce hydraulic potentials (Paterson and Jensen 1984; Sommerfeldt and MacKay 1982; Vander Pluym 1982). Artificial extraction of groundwater through engineered subsurface drainage systems or pumped wells is another method used with some success (Steppuhn and Wall 1997; Beke et al. 1993; Buckland and Hendry 1992; Doering and Sandoval 1976).

The removal of salts from within the root-zone requires the downward movement of water from the surface in saline areas to transport salt out of the root zone. In irrigated areas this is not a problem provided that ample drainage exists beneath the salinized area. Hogg and Tollefson (1992) report the successful reclamation of a salinized irrigated soil near Outlook, Saskatchewan, through the application of large amounts of leaching water following the installation of subsurface drainage. However, in dryland seeps this process is often quite slow because of the small amount of precipitation received in arid and semiarid regions. In a study near Swift Current, Saskatchewan, Steppuhn and Wall (1997) observed that the establishment of tall wheatgrass windbreaks, *Thinopyrum ponticum* (Podp) Barkworth & Dewey, to capture snowfall, combined with the installation of subsurface drainage, could hasten this process.

The use of chemical amendments as remedial tools on salt affected lands is mentioned by a number of authors including Liang and Karamanos 1992; Keren and Miyamoto 1990; and Rhoades 1982; Sandoval and Gould 1978. The application of gypsum, sulfuric acid, and sulfur are sometimes used to provide soluble Ca^{2+} to replace exchangeable Na^{+} in the treatment of sodium affected soils (Keren and Miyamoto 1990). These techniques will have little effect on land reclamation if used on non-sodic soils.

2.2 Subsurface Drainage Technology

The practice of subsurface drainage can be traced back as far as the 2nd century B.C. (Bos and Boers 1994). Since that time subsurface drainage has grown from a practice based on local experience to a complex science. Drainage practices have evolved from creating crude rock-filled openings in the ground to engineered systems of precisely-placed tubing.

2.2.1 Flow to a subsurface drain

Throughout this text the word drainage refers to the artificial removal of excess water within the soil. This task is completed by lowering the water table and preventing its subsequent rise. Flow towards a subsurface drain is generally analyzed by using one of two theories: steady-state or unsteady-state.

Steady-state theory is based on the assumption that the recharge to groundwater is equal to the discharge through the drainage system and consequently a static water table is maintained (Ritzema 1994). The use of steady-state equations is typically applicable only in humid areas with long, medium intensity rainfall (Ritzema 1994).

Unsteady-state theory is based on the assumption that the fluctuation of the water table varies with time. This type of theory is applicable for sporadic recharge events such as high intensity rainfall or irrigation events.

In order for subsurface drains to operate, they must function below the water table; a constraint that suggests the water table cannot be lowered below the depth of the drain. Under unsteady-state conditions where the water table is falling, flow towards a drain is dominantly horizontal (Hillel 1980 and Ritzema 1994). Given the dominantly horizontal flow orientation, the most important factors influencing drain performance are the position of the drains (particularly depth and spacing) and the hydraulic conductivity of the material in between the drains (Hillel 1980).

2.2.2 Types of subsurface drainage systems

There are four main types of drainage systems, open, tubewell, mole and pipe. A complete discussion of each type is given by Cavelaars et al. (1994). Briefly, open drainage is when a deep trench is made to intersect the water table and provide an outlet for excess water. Tubewell drainage is a process of lowering the water table by continuous pumping of a series of wells. Mole drainage consists of a network of unlined circular soil channels. The most commonly used type of drainage is pipe drainage where a system of buried perforated pipe is used to transport excess water to a suitable outlet. The information included within this text is predominantly related to pipe systems, although not exclusively because most types of drainage systems operate under similar principles.

The main configurations used for pipe drainage systems are grid, random and interception (Donnan and Schwab 1974). Grid drainage consists of a number of parallel tubes spaced an equal distance apart that are graded towards a main collector pipe. These types of systems are quite common where the topography is level, and the water table is high over a large area. A variation of the grid drainage system is the herringbone pattern where parallel laterals run into the collector at acute angles. The random drainage configuration is comprised of a system of tubes placed in particular locations due to complex topography or isolated moist areas. An interception drainage system is where single or multiple tubes are placed perpendicular to the predominant groundwater flow direction in an effort to "intercept" any seepage moving down gradient.

The materials used in pipe drainage systems may be clay tiles, concrete pipes, or plastic pipes. Cavelaars et al. (1994) discuss the merits of each material, but for the purpose of this text all subsurface drainage systems mentioned use plastic pipes, as this is by far the most common material. Most modern plastic pipes used for drainage are corrugated for strength and are available in a wide range of sizes. Pipes to be used for laterals are perforated whereas pipes to be used for collectors are not. Depending on soil texture, a drainage envelope may be used around the pipe. An envelope is defined as the material placed around the pipe to act as: (1) a filter to prevent small particles from entering and clogging the pipe; (2) a highly permeable material to lower entrance resistance; or (3) bedding to protect the pipe from uneven soil loading (Cavelaars et al.

1994). Subsurface drain tubing is available directly from the manufacturer pre-wrapped with a thin synthetic material designed to act as a filter. Other common drainage envelope materials may include gravel or industrial waste products such as slag or shredded tire pieces (Thomas et al. 1998; Cavelaars et al. 1994).

2.2.3 Drainage investigations

Before any drainage installation is undertaken a comprehensive study should be completed at the site of interest to quantify important properties such as soil properties, site hydrology, and drainability (van Aart and van Alphen 1994). Initial reconnaissance includes the examination of aerial photographs, soil maps and other survey publications. The installation of piezometers and water wells is often helpful in obtaining information on seasonal groundwater levels, estimating groundwater recharge rates, and determining the direction of groundwater flow. Obtaining soil samples throughout the depth of interest is useful for determining the relative permeability of soil layers, the occurrence of macropores, and assessing the need for a drainage envelope. An assessment of the drainability of the site is completed to determine an optimal place to discharge the drainage effluent water, estimate the hydraulic conductivity of the soil layers, and reveal any problems that may be encountered during the installation. The amount of effort put into a drainage investigation is dependent on the size of the drainage project and the amount of money available for a particular drainage project. It will also vary among humid and arid regions, as the reason for drainage is often unique to a particular area.

2.2.4 Installation methods

The most common machines used for the installation of subsurface drains can be divided into two classes: trenchers and trenchless machines (Cavelaars et al. 1994).

Trenchers can vary from attachments placed on small rubber tire machines to dedicated, large, track driven machines. The excavation implement is usually a continuous chain or a wheel with a series of knives attached to it. In some cases the excavation can be done using a hoe-type attachment. A major disadvantage of most trenchers is the slow speed of operation and the lack of ability to work in rocky soils.

Trenchless machines are capable of placing drain tubing down to considerable depths by creating a tunnel in the ground and simultaneously place tubing in the ground without excavation (Kanwar et al. 1986). The blade is designed to lift and slit the soil as the machine moves forward. The slit closes and the soil falls back around the pipe after the machine has passed. The main advantage of a drainage plow is the relatively high speed at which it is capable of installing pipe to a considerable depth. A disadvantage is that while working at large depths in wet soils the draught becomes sufficiently high that a separate winch machine is necessary for many jobs (Paterson and Jensen 1984).

A comparison of the long-term performance of trench and trenchless drain installations by Mirjat and Kanwar (1992) reported that no significant differences in water table positions or drain outflow rates were observed after a 10-year period.

A problem with all methods of drain installation is that the cost greatly increases with depth (Jensen 1982). The large machinery required to achieve these depths on a commercial scale is very costly to operate and transport. In some cases the cost of transportation is the largest component of a drainage project (E. Jensen, Drainage Consultant, Olds, Alberta).

Paterson and Jensen (1984) state that a laser grade control should be used on all installation equipment to ensure that the drains will function properly.

2.2.5 Drainage criteria for dryland salinity

Ideally the depth and spacing of a drainage system is set according to the results of a design equation. These equations are often used successfully in humid or irrigated areas yet do not lend themselves particularly well to dryland seeps. Due to the relatively small size and complex geology of a dryland seep the basic assumptions used in these design equations are not usually met. Rather, drain depths and spacing are often based on local experience and "rule of thumb" values. Buckland and Harker (1986) state that, in Alberta, drainage depths are based on field investigations, and drain spacing is estimated based on an inferred hydraulic conductivity derived from soil textural characteristics. Overall, there is a general lack of available information regarding drainage design in western Canada.

2.3 Drainage Testing

Drainage system testing implies a comparative investigation of one or more properties that may affect drain performance. Some of the variables investigated in the literature are installation methods (Kanwar et al. 1986), materials (Thomas et al. 1998), design factors such as drain depth and drain spacing (Madini and Brenton 1995; Buckland and Harker 1986), or a combination of these.

Oosterbaan (1994) suggests that the effects of drainage may be direct or indirect. The direct effects of a drainage system are a reduction in the amount of water stored within a soil and a discharge of water from the system. Fittingly, the properties most often examined are water table position and drain outflow. Buckland and Hendry (1992) and Mirjat and Kanwar (1992) provide examples of common direct measurement techniques. An indirect effect is any observed difference imparted by a direct effect of a drainage system. Examples of some indirect effects measured are changes in soil salinity (Steppuhn and Wall 1997; Buckland and Hendry 1992; Buckland and Harker 1986), soil moisture regime (Beke et al. 1993), and crop yield (Bolton et al. 1980).

2.3.1 Drainage efficiency

Oosterbaan (1994) states "The objectives of agricultural drainage are to reclaim and conserve land for agriculture, to increase crop yield, ... and/or to reduce the costs of crop production in an otherwise water logged land." In drainage system testing, the ultimate goal is to determine what type of systems could achieve the aforementioned objectives with a minimized degree of cost/effort.

2.3.2 Evaluation of the direct effects of drainage

The direct effects of a drainage system are a reduction in the amount of water stored within a soil and the discharge of water from the system. Therefore, the obvious measurable features of drainage performance are water table position, and drain discharge flow rates and volumes.

There have been a number of different methods used to evaluate the performance of a drainage system with respect to water table control. Most often, a drainage system comparison is set up with identical plots containing different treatments. Water table positions as they vary with time after significant hydrologic events, such as irrigation or rainfall, are then used to compare the treatments (Thomas et al. 1998; Buckland and

Hendry 1992; Kanwar et al. 1992). In other cases, field performances of different drainage treatments are compared to the performance predicted by drainage equations or other mathematical models (Buckland and Harker 1986; El-Mowelhi and Hermsmeier 1982). Buckland and Hendry (1992) also used a nest of tensiometers above the water table to measure and compare the size of gradients between different drainage treatments.

Drain discharge flow rates are also commonly looked at as a performance indicator of drainage systems. For example, Madani and Brenton (1995) use drain discharge flow rates, as well as discharge per hectare of test plot as methods of rating the hydraulic performance of drainage systems of different spacing. Similarly, Mirjat and Kanwar (1992) used total monthly drain flow, and also drain flow expressed as a percentage of rainfall, as comparative measures for testing differences between trench and trenchless installation methods.

2.3.3 Evaluation of the indirect effects of drainage

Drainage system comparisons are sometimes also based on indirect effects. However, indirect effects are generally more difficult to use comparatively, because they are affected by more than just the direct consequences of drainage. For example, lowering the water table under a dryland saline seep does not always result in a reduction in salinity and an increase in yield (Buckland and Hendry 1992). In their study, the average EC_e of the soil profile (0-1.2 m) was found to be 104 % of the original level three years after drain installation, with no leaching water applied. Indirect effects can often indicate the performance of the drainage system as a whole and should not be dismissed by researchers. In many cases, the indirect effects are perceived to be more important and are more frequently sought by the landowner than the direct effects. For example, increased crop yield and land workability are more important to producers than drain effluent volume.

Beke et al. (1993) examined the spatial and temporal distribution of soil moisture to compare the positions of three interceptor drain lines in a saline seep and found that subsurface interception drainage significantly affected the soil-water regime at different distances from the drains. Buckland et al. (1986) monitored changes in soil salinity between drainage treatments of varying depths and used this information for a comparative study. This study indicated that, after two years of leaching with irrigation water, soil salinity of the 0-2 m profile ranged from 74 - 114 % of original levels depending on the depth of the drain lines and the amount of water applied.

3. MATERIALS AND METHODS

3.1 Project Description

The project described in this thesis is part of an ongoing long-term research project being conducted by Agriculture and Agri-Food Canada (AAFC). Researchers from the AAFC Semiarid Prairie Agricultural Research Centre (SPARC) have been conducting various tests at this site from 1984 until present. Since 1997, researchers from the University of Saskatchewan have collaborated with AAFC in field studies at the site, technical support, and data analysis. The study described in this thesis involves the use of data from the entire time period that AAFC has been doing work at this site. Pre-1997 data collection, site installations, and laboratory analysis were completed exclusively by AAFC. For years 1997-1999, data collection and site installations were completed jointly by AAFC and the University of Saskatchewan with funds supplied through AAFC. All laboratory analysis, for all years, was completed at SPARC laboratories, and SPARC personnel collected weather data. All data analysis used in the creation of this text was compiled at the University of Saskatchewan.

3.2 Site Description

The study site consists of a 65-ha field located 4 km southwest of Swift Current, Saskatchewan (NW 11-15-14 W3). Two similar saline areas, approximately 1 ha each, occur in the centre of the study site (Figure 3.1). A slight rise in topography separates the two parcels. The slightly undulating land surface slopes approximately 3 % to the southeast with drainage directed towards the Swift Current Creek. The two seep areas often form impassible waterlogged areas in the spring that later dry and exhibit white salt crusting on the surface (Figure 3.1). A gully-like depression to the northeast of the north seep area also shows signs of soil salinity (as seen by poor crop growth and salt crusting) but is not included as part of the research program. Throughout the scope of this text, the two saline areas will be referred to as the north (experimental drainage treatment) and south (traditional drainage treatment) parcels as depicted in Figure 3.1.

The landform at the study site consists of a thin, partially eroded veneer (25 cm) of loess overlying glacial till. The topsoil is classified as a Saline Brown Chernozem. The entire site was continuously cropped to barley throughout the entire study.

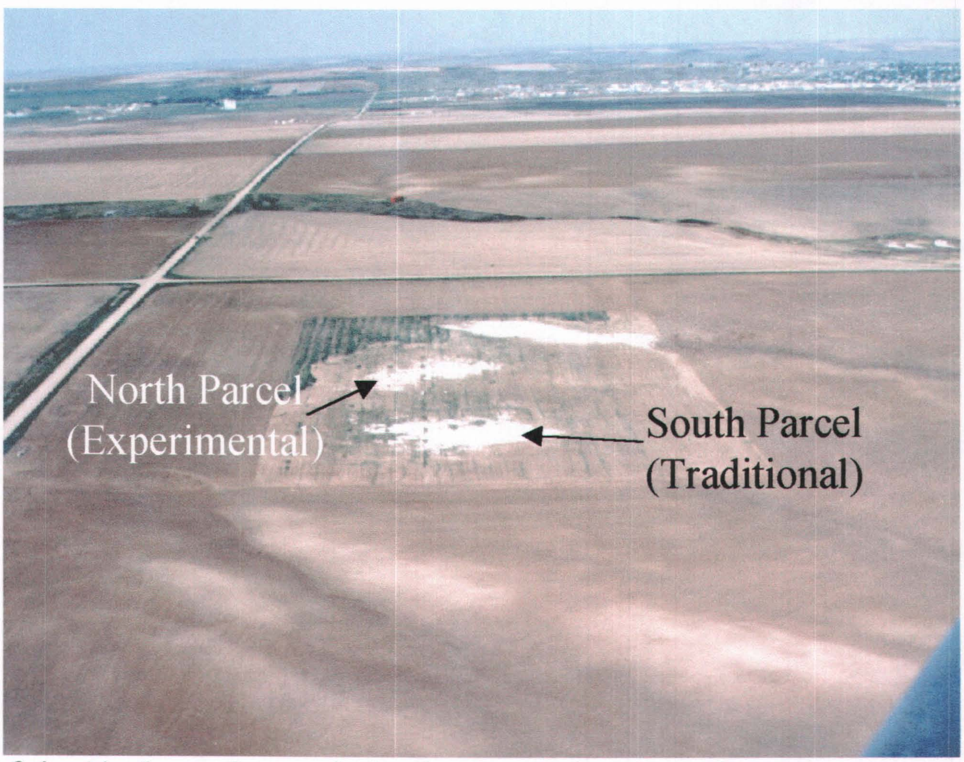


Figure 3.1: Air photo of research site showing the locations of seep areas.
Note: Photo was taken during spring 1987 facing directly north. (Photograph courtesy of H. Steppuhn)

3.3 Experimental Design

3.3.1 Traditional drainage system

The traditional drainage system (Figure 3.2) was installed in the fall of 1990. It consists of six parallel 100-m long laterals running from north to south at a 1 % grade. Spacing between the laterals was set at 15 m and the depth of the pipes range between 1.52 - 1.83 m. The total length of perforated drainage tubing installed is estimated at around 540 m. The materials used are 100-mm diameter, perforated, corrugated plastic tubing with a pre-installed synthetic filter “sock”. Flow from the laterals is directed towards a 150-mm, non-perforated, corrugated collector pipe running west to east. The flow is measured at the underground measuring station and is then diverted to a down-slope settling basin located to the southeast of the study site (not visible in Figure 3.2).

This system was installed using a track driven ladder-type trencher equipped with a laser guided grade control (Figure 3.3). The areal extent of the drainage system was selected at the contractors own discretion. Drain line spacing was also selected according to the contractor’s judgement as no measurements of hydraulic conductivity were made.

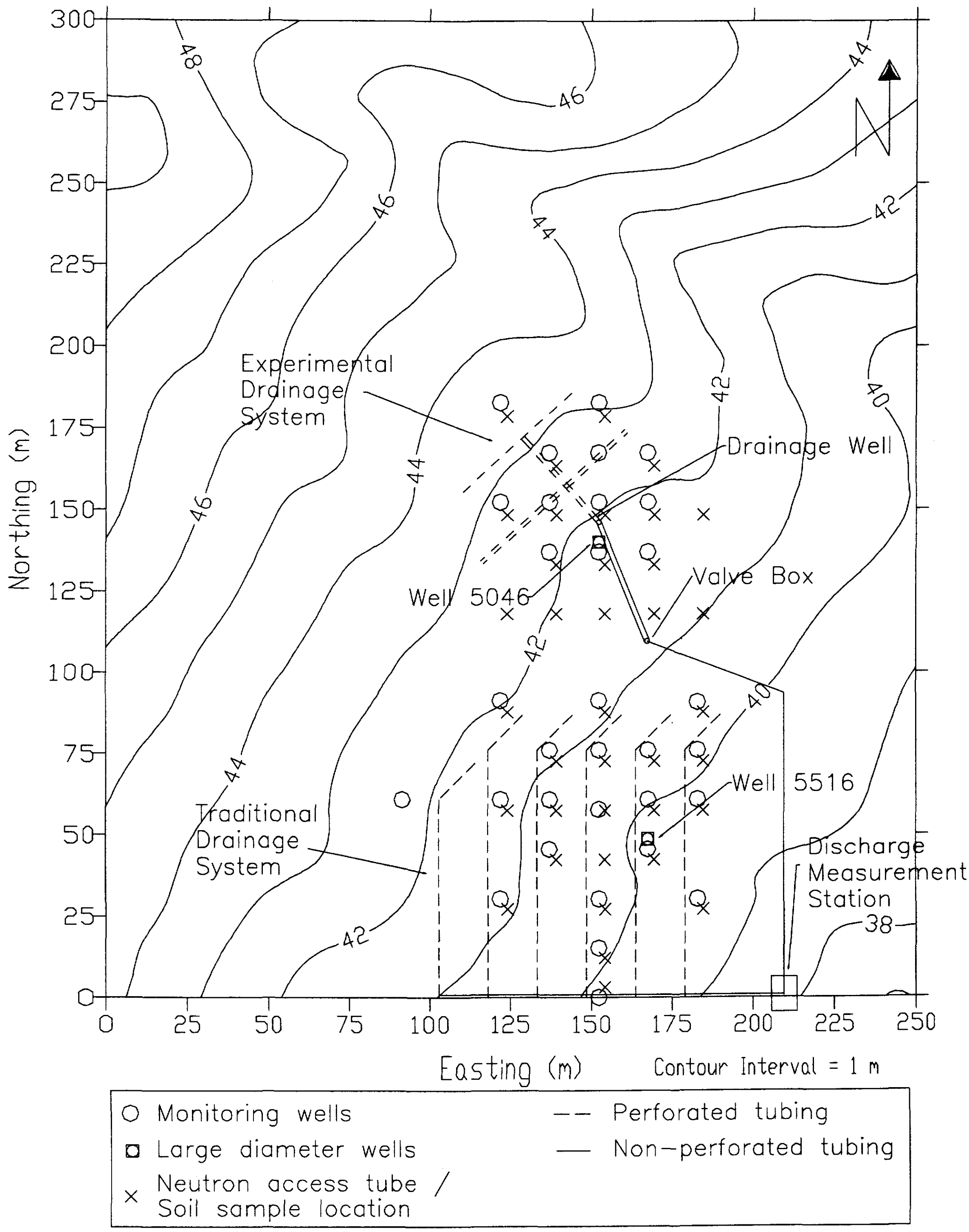


Figure 3.2: Topographic map of site showing location of drainage lines and sampling locations.

Note: Contour elevations are given in metres above some arbitrary datum. Double lines shown for the experimental system indicate the location of the deep option.

Figure 3.3: Installation of traditional drainage system using track-driven ladder trencher. (Photograph courtesy of H. Steppuhn)

3.3.2 Experimental drainage system

The collector for the water harvesting system in the north parcel actually consists of two separate test drainage designs super-imposed on one another. This is a test concept that represents two separate drainage systems that would be installed individually in practice. This idea allowed researchers to evaluate two separate design options with only one installation. Both systems were surveyed with a surveyor's level and installed using a rubber-tire excavator (Figure 3.4). The lines from both depths run into a collection/observation well located at the southeast corner of the seep. At this point the systems flow to the discharge measuring station through solid polyvinyl chloride (PVC) conduits. A separate valve controls each depth so that they can be operated individually. Even though the two systems are constructed at different depths they are considered to be equal in terms of installation effort. Deeper systems take longer and are more costly to install, therefore, the length of tubing used was reduced to correspond to requiring an equal effort as the shallower system. The layout of the experimental drainage system can be seen in Figure 3.2. The location of the experimental system was judiciously selected as to be up-gradient of the area exhibiting a near surface shale layer. Figure 3.5 shows a side profile of the experimental drainage system illustrating the two depth options and the drainage well. The experimental system discharge was directed to a trickle irrigation system for most of the study period. This irrigation system is located to the east of the north parcel and cannot be seen in Figure 3.2.

Figure 3.4: Installation of experimental system using rubber-tire back hoe. (Photograph courtesy of H. Steppuhn)

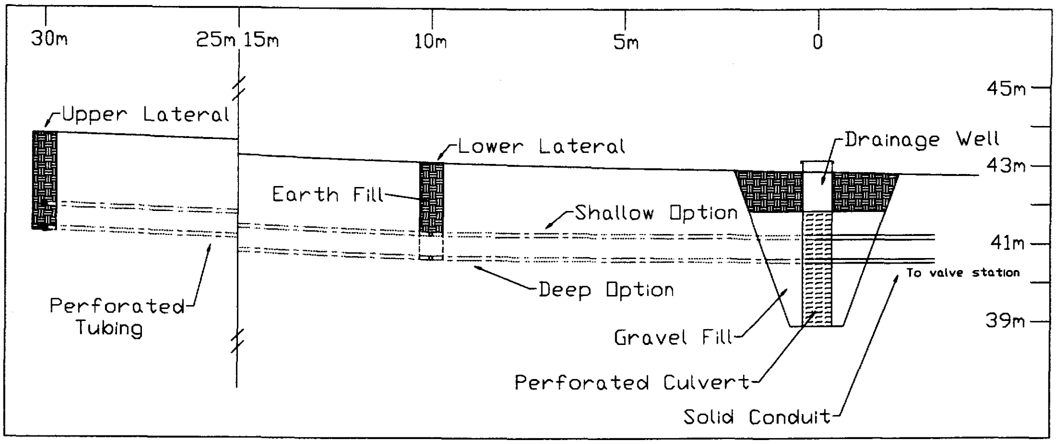


Figure 3.5: Side profile of experimental drainage system.

a) Shallow option

The shallow system is installed at a depth of 1.83 m. The system is comprised of a main lateral extending up-slope from the drainage well, and four sub-laterals extending perpendicular to the main lateral giving the system a characteristic I-beam shape. The system consists of 135 m of 100-mm, perforated, corrugated, filter-wrapped tubing installed at a 1 % grade. The trench was back-filled with earth and then compacted from the surface. Dimensions of the experimental system can be found in Appendix A.

b) Deep option

The deep system is installed at a depth of 2.44 m and follows a similar pattern as the shallow system with the exception that the northwest sub-laterals were removed resulting in a cross-shaped configuration with a total of 90 m of perforated tubing. A depth of 600 mm of washed, crushed rock (19-mm) was placed around and on top of the pipe constituting the space in the trench between the deep and shallow systems. The width of the trench is approximately 610 mm. The purpose of the artificial fill was to increase drainable porosity and storage. The porosity of the gravel fill is approximately 0.45 m^3/m^3 (determined experimentally). Laterals for this system are constructed from the same material as used in the shallow system. Dimensions of the experimental system can be found in Appendix A.

3.3.3 Instrumentation

a) Discharge measurement

All discharge measurements were conducted at the underground measuring station. Flows from the traditional drainage system were measured by a 15° v-notch weir constructed in the middle of a large flow box. Flow from the drain line poured into the upstream end of the box and then passed through the weir into the downstream section of the box where the water exited towards a downstream settling basin. A baffle was constructed between the discharging drain line and the upstream stage recorder to negate the effects of the splashing water on the measurement device. A stage recorder was used to translate the position of a float resting on the upstream water surface as it varied with time to an 8-day paper chart. The weir was calibrated by taking actual measurements of flow rate and hydraulic head and developing an equation that could be used to relate the recorder-measured head to discharge rates.

Flows from both experimental drainage systems operating in the north parcel were measured by using an in-line turbine flow meter (Omega FTB-4607, Omega Engineering Inc., Laval, PQ). A data logger (CR7, Campbell Scientific Canada Corp., Edmonton, AB) was used to record the output from this meter at 15 minute intervals.

b) Potentiometric surface monitoring

Monitoring wells were installed in 1985 and 1986 (by Agriculture and Agri-Food Canada personnel) on a grid system throughout the entire site and are intensely concentrated in the two seep areas (Figure 3.2). The depth of these wells varies from 2 to 6 m. Water wells were constructed from 25-mm PVC pipe that had been perforated for a length corresponding to a distance measured from the bottom of the hole to approximately 0.75 m from the soil surface. Perforations were made in the well by drilling 4-mm holes through the diameter of the well at 150-mm increments. Cheese cloth or synthetic drainage filters were wrapped around each standpipe to prevent the wells from filling with small particles. Gravel (6 mm) was poured into the hole around the standpipe up to 1 m from the surface. Auger cuttings from encountered impermeable layers were compacted around the standpipe to prevent the development of preferential flow paths from near surface water travelling down the borehole.

A large demonstration/monitoring well was installed in the north parcel at the southeast end of the experimental drainage system (Figure 3.5). Throughout the text this well is referred to as the drainage well. Construction materials include a 760-mm galvanized steel road culvert placed vertically to a depth of approximately 4 m. Perforations were made in the culvert by drilling 50-mm holes throughout the buried depth. The well was installed by excavating a large pit with a back-hoe, placing the culvert on end and then installing 19-mm crushed rock near the well and filling the hole with soil.

The potentiometric surface in the two 250-mm wells (5046 and 5516, Figure 3.2) and the large drainage well located in the north parcel were continuously monitored by using stage recorders equipped with 8-day paper charts. The smaller diameter observation wells and piezometers were measured intermittently by using a two-conductor electric tape. The frequency of these observations was dependent on the activity of the water table, but generally measurements were made weekly in all wells.

3.4 Experimental Procedures

3.4.1 Hydrological investigation procedures

For the purpose of this study, a limited group of wells were selected to represent the performance of each parcel. To overcome the fact that the two systems were of different sizes, the group of monitoring wells selected for each parcel was limited to those within a boundary surrounding each drain system. The boundary limits were set as to include all of the wells located within the drain system and those within one drain spacing away from the drain system. The wells that fit this criterion are shown in Figure 3.2.

Mean water table elevations of each parcel were the expressions selected to represent the hydrologic characteristics of each parcel because of the averaging effects of the drainage systems. Each drainage system resulted in a single flow being measured, in effect averaging the performance of each drain line throughout the entire parcel. Therefore, assessment of each individual well is not as important as the performance of the entire group of wells.

The mean water table elevation was calculated for all dates when a minimum of 75% of the wells within the selected group were measured and recorded. For example, the south parcel has 21 monitoring wells within the defined boundary, mean water table elevations were calculated for all dates that 16 or more wells were measured. This criterion was established because, occasionally, not all of the wells within a parcel were measured on the same day due to technical difficulties or staffing limitations. The wells being measured on any given day were not prejudiced with respect to location throughout the parcel. A frequency histogram indicated that the majority of the days had over 75% of the wells measured. This point was chosen to include as many measurement dates as possible while attempting to use a sufficient number of wells to obtain an accurate average water table elevation calculation.

3.4.2 Soil moisture investigation procedures

Soil moisture measurements were made during 1998 in both parcels. The neutron thermalization technique (Topp 1993) was used to measure volumetric water content of the soil at 10-cm depth increments to a depth of 180 cm. The locations of the access tubes are shown in Figure 3.2. The access tubes used were constructed from galvanized pipe and were installed by AAFC. Prior to each measurement date the tubes were inspected for seepage water and bailed out if necessary. During 1998, the south parcel had a crop growing in it whereas the north parcel did not. In order to reduce the effect of this inequality, an area with a radius of 1.0 m from the center of each neutron tube was kept vegetation free in each parcel. Topp (1993) states that the radius of measurement of this technique ranges from about 0.15 m for saturated soil to over 0.60 m for dry soil. An additional effort was made to control the growth of large plants whose rooting systems would likely extend into the zone of measurement.

3.4.3 Hydro-chemical investigation procedures

Water samples were collected every spring and fall (1988-1999) from monitoring wells within each parcel. Wells selected for sampling were the same as those identified in Figure 3.2. For this operation, hand pumps were used to extract approximately 1.5 litres of water, thereby sampling over the integrated screen area of the well. The water samples were then analyzed for EC, pH, SO_4^{-2}, Cl^-, Na^+, K^+, Ca^{2+}, and Mg^{2+}.

Drain discharges were also sampled and analyzed for the same constituents as the monitoring wells. The frequency of these samples ranged from daily to weekly depending on flow rates of the system.

3.4.4 Soil chemical investigation procedures

During September or October of years 1988-1999, annual soil sampling was completed throughout the site. Sites selected for soil sampling are shown in Figure 3.2, near the neutron meter access tubes. Note that the boundaries chosen for each parcel were different from the ones established for the hydrological investigations. Rather, in this case, the boundaries were extended to the edge of the severely salinized area so that the measured area was roughly the same in each parcel. This was done in order to determine if the smaller, experimental system would have as great of an effect on soil salinity levels as the traditional drainage system; one of the original goals of this research project.

The samples were obtained using a coring tool mounted on a one-ton truck body. Sampling tubes were pushed down to a depth of 90 cm, brought back up to the surface, and the material sub-sampled into 15-cm intervals. The saturated paste extract method was used and analysis completed for EC_e, pH, SO_4^{-2}, Cl^-, Na^+, K^+, Ca^{2+}, and Mg^{2+}.

3.4.5 Initial site characterization procedures

In 1985, an intensive sampling program was completed on a 15-m grid spacing throughout the majority of the site. Soil cores were obtained from a 180-cm depth and then sub-sampled at the following depth intervals: 0-10, 10-20, 20-30, 30-45, 45-60, 60-75, 75-90, 105-120, 135-150, and 165-180 cm. These samples were then analyzed for soil texture (hydrometer method), bulk density, and analyzed for EC_e, pH, SO_4^{-2}, Cl^-, Na^+, K^+, Ca^{2+}, and Mg^{2+}. The purpose of this sampling program was to characterize the site and establish any differences between the two parcels. The sampling grid used for initial characterization is slightly different, but more comprehensive, than that used during annual soil sampling (locations can be found in Appendix B).

3.4.6 Saturated hydraulic conductivity testing procedures

In 1999, saturated hydraulic conductivity tests were completed in some of the wells found in each parcel. The locations of the wells selected for testing can be seen in Figure 3.6. For this, the Bouwer and Rice (1976) slug test method was used, where a volume of water was instantaneously extracted from a well and then water level recovery measurements were recorded. Calculations of hydraulic conductivity were then completed by analyzing the time-water level recovery data. A repeatability test was also done as a measure to check the reliability of the results.

3.4.7 Geological characterization

Characterization of site stratigraphy was completed while monitoring wells were being installed. Transects that were used for this study are shown in Figure 3.6. Auger cuttings were brought to the soil surface, characterized visually, hand-textured and recorded by the driller. Samples were collected for textural and chemical analysis at every distinct textural change.

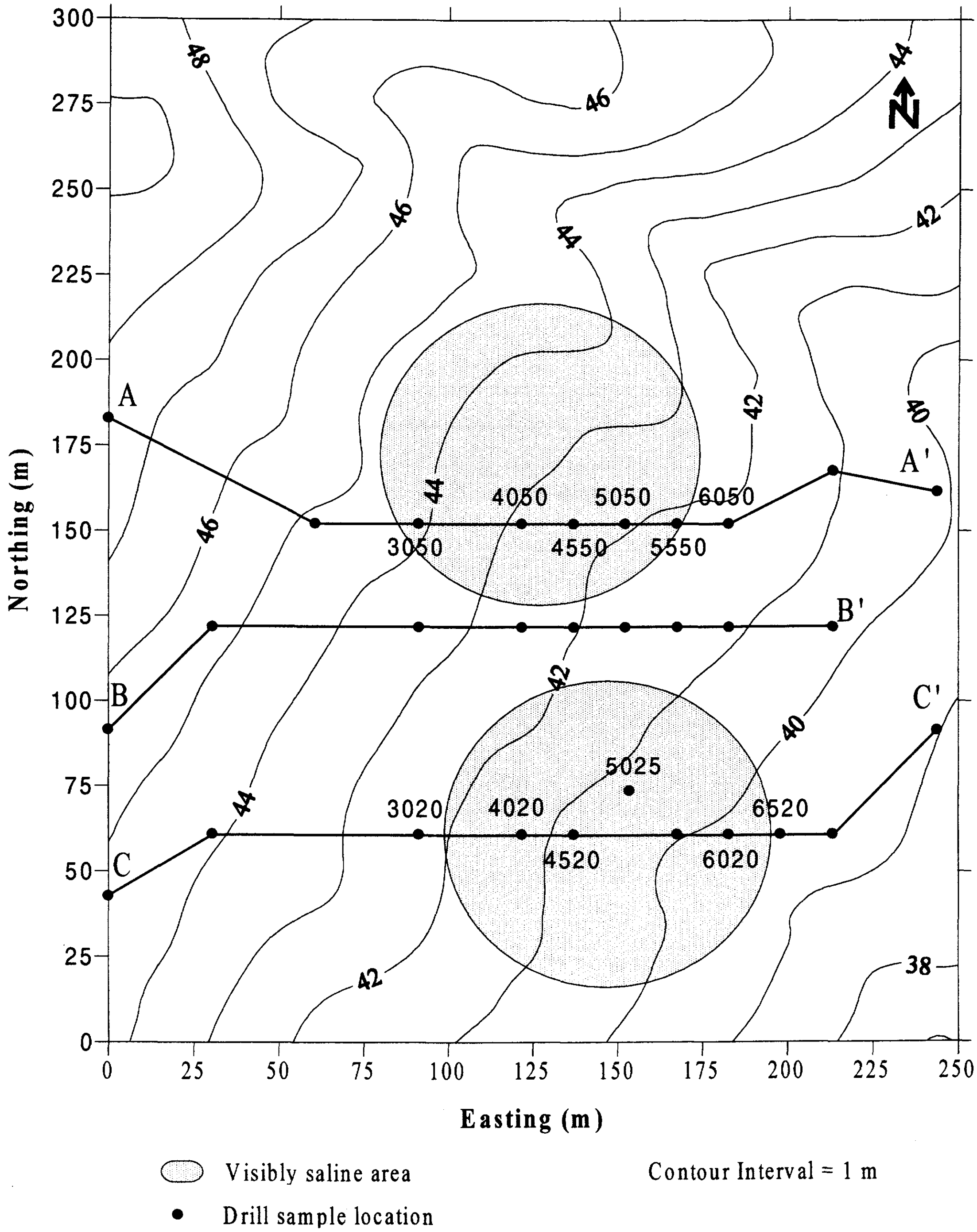


Figure 3.6: Location of transects used for geologic characterization.
Note: Wells with ID labels were used for hydraulic conductivity measurement.

3.5 Analytical Procedures

The procedures used to analyze the water samples and saturated paste extracts are given in Table 3.1.

Table 3.1: Laboratory chemical analysis procedures.

Analyte	Procedure
EC_e	Electrical conductivity cell
pH	pH probe
SO_4-S	Methylthymol Blue
Cl	Ferric Thiocyanate
Ca, Mg, Na, and K	Atomic Absorption

Source: Adapted from Winkleman (1987)

4. RESULTS

4.1 Climate

The climate of the area is continental and semiarid. Mean annual precipitation during the study period was 370 mm and mean annual temperature was 4.3°C (1985-1998). Weather data was obtained from the SPARC meteorological station located 6 km east of the study site. Values of monthly precipitation, temperature and calculated potential evapotranspiration for years 1985 to 1999 can be found in Appendix C.

Seasonal precipitation values as well as period averages of precipitation and temperature are given in Table 4.1 for hydrologic years 1986 to 1999. Season intervals are divided into autumn (August through October), winter (November through February), spring (March through April), and summer (May through July). The summer and autumn season intervals were selected so that the summer period reflected the crop growing season and autumn represented the warm period after the crop is taken off until snow fall. In southwestern Saskatchewan, barley crops are often mature at the end of July and harvested in August. Therefore, it was decided that the month of August should be included in the autumn season rather than in the summer season.

Presented in Figure 4.1 are the estimated water deficits for two periods: the growing season (May through July); and the warm season (April through October). The growing season deficit, although included in the warm season estimate, is presented separately because of the effect that climate has on crop growth. However, the entire warm season deficit is better used to evaluate the effect of climate on soil salinization. The potential evapotranspiration values were estimated based on the mean monthly temperature and latitudinal location using the Thornthwaite (Gray 1970) method. Important features of the May-July series are the water surpluses observed in 1991 and 1999, where precipitation was larger than the potential evapotranspiration. With respect to both series, there is a noticeable difference in climate before and after 1991. For example, before 1991 there are four years that experience a warm season deficit (April-October) greater than 250 mm, whereas no single year after 1990 is that dry. The year of 1990 is an important transition point because it marks the time of installation of the traditional drainage system.

Table 4.1: Seasonal and average weather information recorded at a nearby weather station (SPARC weather station - 50°16-N 107°44).

Year	**Seasonal precipitation (mm)**			
	Winter (Nov-Feb)	**Spring (Mar-Apr)**	**Summer (May-Jul)**	**Autumn (Aug-Oct)**
1986	52	22	205	124
1987	<u>33</u>	38	<u>118</u>	<u>58</u>
1988	<u>29</u>	<u>12</u>	<u>143</u>	68
1989	70	39	**210**	120
1990	52	40	<u>159</u>	<u>25</u>
1991	59	**64**	**302**	60
1992	38	<u>16</u>	182	96
1993	39	48	175	**225**
1994	**76**	<u>16</u>	160	76
1995	30	**59**	189	**196**
1996	**86**	37	166	**150**
1997	**85**	**79**	163	84
1998	<u>23</u>	32	166	103
1999	75	45	**240**	<u>36</u>
Ave Precip.	102	53	184	102
Ave Temp (°C)	-8.1	1.5	15	12

Values in bold font represent the three highest recorded precipitation amounts, values underlined represent the three lowest precipitation amounts.

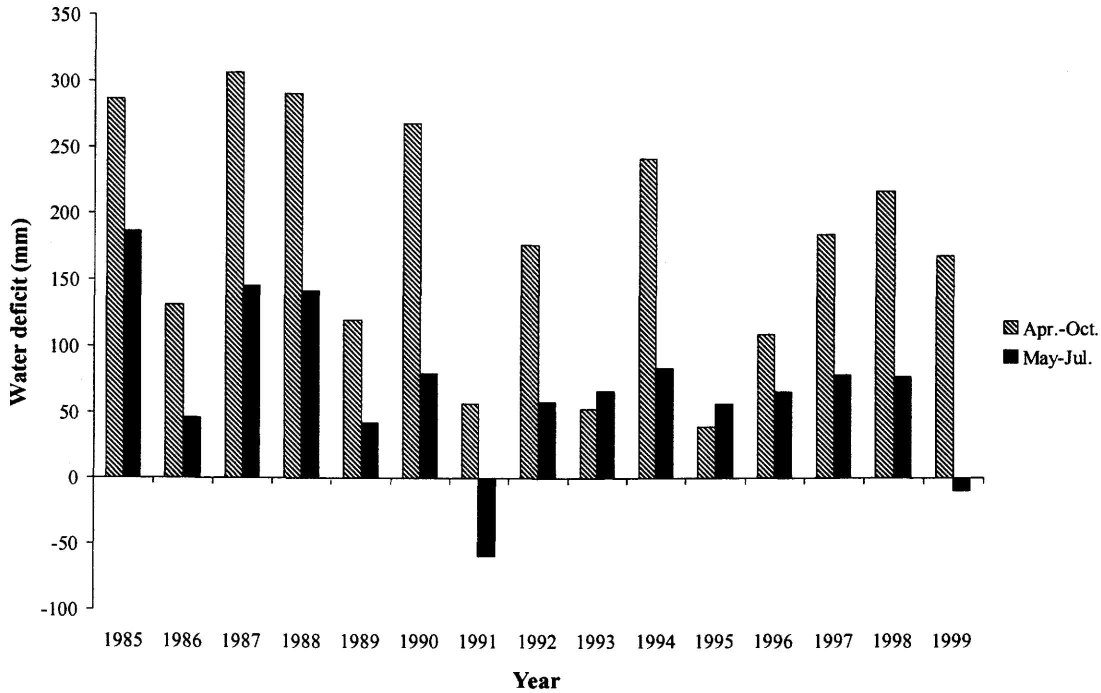


Figure 4.1: Seasonal water deficits for warm season (Apr.-Oct.) and growing season (May-Jul.).

4.2 Baseline Conditions

4.2.1 Physical characteristics

a) Geological properties

*i. **Factors contributing to saline seep development***

The subsurface stratigraphy is generalized in Figure 4.2, for three cross-sections A-A', B-B', and C-C' (Figure 3.6) cutting through the north parcel, between the two parcels, and the south parcel, respectively. Glacial till underlies the loess veneer characterizing the surface of the site. The texture of this till layer is quite variable, ranging from a silty loam on the west side of the saline parcels to a loamy clay on the east side. Sand lenses occur in scattered positions throughout the depth of the till to the west of the saline parcels. Beneath the till, lies a near surface shale bedrock layer, believed to be part of the Bearpaw formation. The depth to this relatively impermeable layer ranges from over 3 m on the west boundary of the saline parcels to less than 1.5 m on the east side (Steppuhn and Wall 1997). The till-shale contact, is much coarser textured than the overlying till and the underlying shale. Researchers from SPARC have concluded that the textural transition of the till, along with the occurrence of the near-surface shale layer have caused the salinization associated with this site (H. Steppuhn, Research Scientist, Swift Current).

ii. ***Saturated hydraulic conductivity***

Saturated hydraulic conductivity results, obtained from slug tests completed in 12 monitoring wells, are shown in Table 4.2. The location of these wells can be found in Figure 3.6, and the analysis can be found in Appendix D. Three consecutive measurements were made on wells 4020 and 4520, and two measurements on 6520 to test the repeatability of the method, as a measure of reliability (Table 4.2 accompanying note). These observations indicate that the method used is accurate enough for this study, as the ranges of results found in the single well tests were much smaller than the ranges observed for the entire parcel. The slug test method tests a volume of the soil formation immediately below the water table. The depth tested for each well can be seen in Figure 4.2.

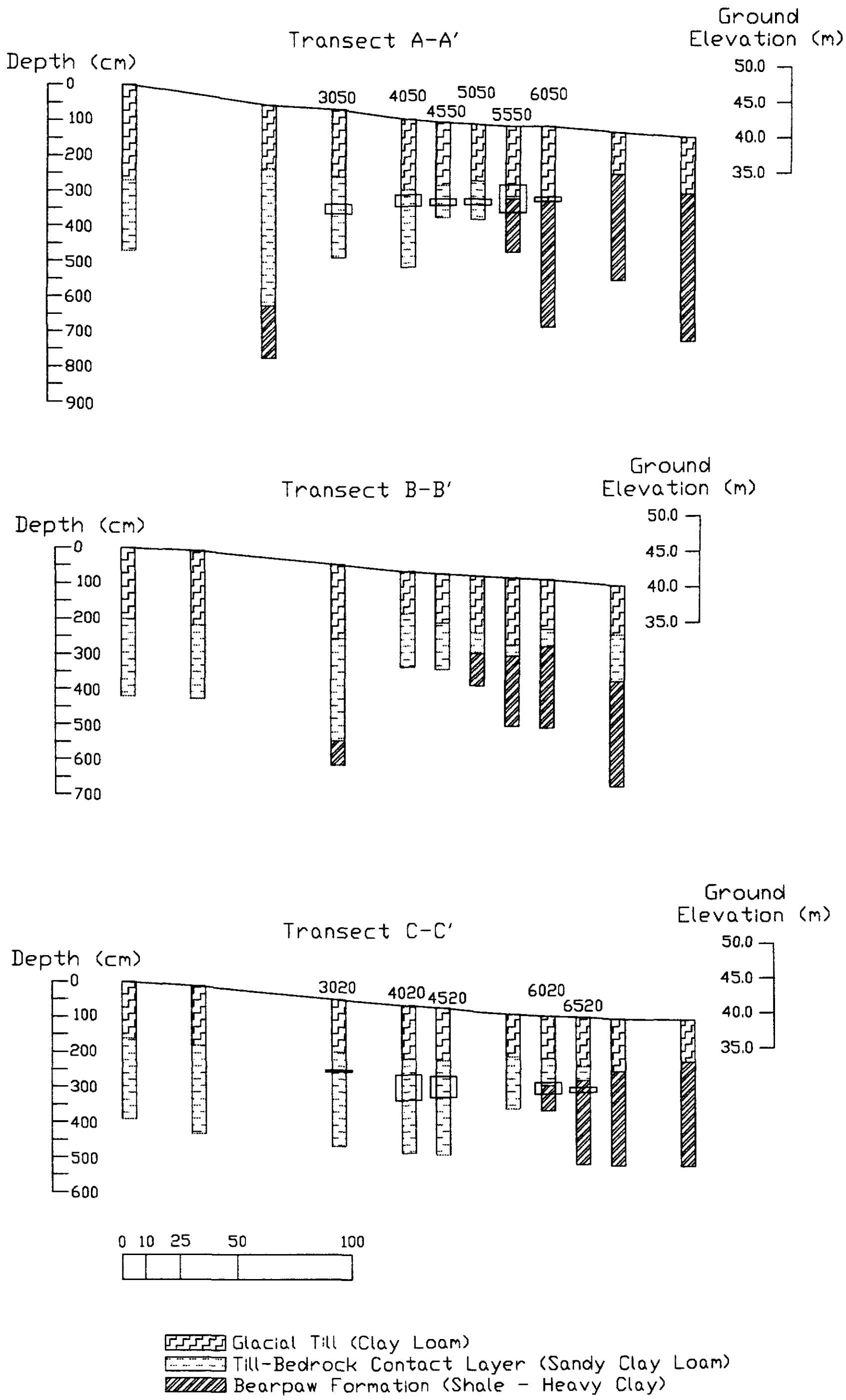


Figure 4.2: Stratigraphy of cross sections A-A' (North Parcel), B-B'(non-salinized area between parcels), and C-C' (south parcel).

Note: Locations of cross sections can be found in Figure 3.6. Rectangles indicate the depth of testing for hydraulic conductivity measurement.

The average hydraulic conductivity measured from wells located in the north parcel was found to be significantly different (α=0.05) and is approximately one order of magnitude lower than the south parcel average (Table 4.2). Tests in the north parcel exhibited a larger degree of variation as the results were seen to vary over two orders of magnitude whereas the south parcel only varied by one order of magnitude.

Table 4.2: Saturated hydraulic conductivity results.

South Parcel			North Parcel		
Well I.D.	**K_{sat} (m/s)**	**Depth (m)**	**Well I.D.**	**K_{sat} (m/s)**	**Depth (m)**
3020	1.04E-07	2.02-2.08	3050	2.26E-06	2.68-2.95
4020*	4.92E-06	1.96-2.70	4050	4.32E-07	2.14-2.34
4520**	4.58E-06	1.95-2.54	4550	5.35E-08	2.17-2.35
5025	3.23E-06	1.85-2.24	5050	2.57E-07	2.19-2.28
6020	1.37E-06	1.90-2.23	5550	3.36E-07	1.67-2.45
6520***	1.69E-06	2.21-2.98	6050	7.50E-08	1.99-2.14
AVE	*1.61E-06*		*AVE*	*2.64E-07*	

* 4020 individual test results: 4.60, 5.31, 3.57 (1.0×10^{-6} m/s)
** 4520 individual test results: 3.57, 5.68, 4.74 (1.0×10^{-6} m/s)
*** 6520 individual test results: 1.12, 2.54 (1.0×10^{-6} m/s)

b) Soil properties

*i. **Soil texture***

A summary of the mean particle size distribution expressed as percent clay sized, and sand sized particles is given in Figures 4.3a and 4.3b. Overall average soil texture at the site ranged from clay loam to clay. This information is based on the initial site characterization sampling and laboratory analyses completed by Agriculture and Agri-Food Canada personnel in 1985.

Excluding the upper 30 cm, clay content (Figure 4.3a) changed with depth by less than 10% for both parcels. The north parcel had slightly higher clay contents in the middle depths, while the south parcel had higher clay content at deeper depths.

Sand content (Figure 4.3b) in both parcels tended to increase with depth, to over 40 % below depths of 150 cm. The percentage of sand is significantly different between the two parcels with the exception of depths between 105 and 150 cm. Also, as indicated by the standard deviations (Appendix D), the sand content tended to be more variable than the clay content. This variation was much more prevalent in the south parcel than in the north parcel.

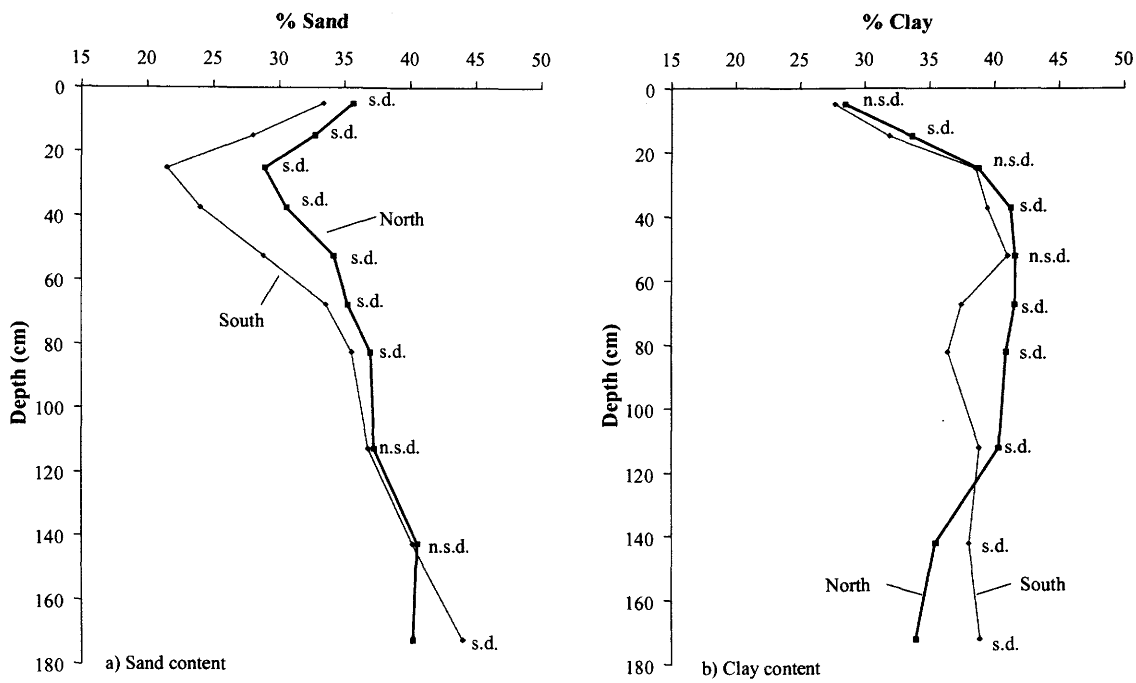


Figure 4.3: Soil texture (a) average sand content, (b) average clay content.

Note: Number of samples used in calculation of average varied from 14-28 (north parcel) and 13-39 (south parcel) depending on depth. Abbreviations s.d. and n.s.d. following data points indicate whether or not the two parcels are significantly different (t-test, $\alpha = 0.05$).

ii. ***Bulk density***

A comparison of mean bulk density (ρ_b) values for the two saline parcels, obtained during the summer of 1985, is presented in Figure 4.4. Due to the difficulties associated with sampling to depth in moist soils, the number of samples averaged is different between the two parcels and also among the various depths in each parcel. The number of samples taken in the south parcel ranged from 36 at the surface to 23 at depth. Similarly, the number of samples taken in the north parcel ranged from 33 at the surface to 17 at depth. High water tables were frequently observed in both parcels during this period. Locations of the sampling points used for initial physical characterization are indicated in Appendix B.

Average bulk density values for the entire 0-180 cm profile were 1.41 g/cm^3 and 1.51 g/cm^3 for the south and north parcels, respectively. Values were significantly different (α=0.05) between parcels for all depths except for the top 10 cm (Figure 4.4). The difference between the two parcels was quite considerable for all depths under 70 cm. Variation was greatest among the deeper depths while shallower depths varied considerably less (Appendix D).

4.2.2 Chemical characteristics

Soil samples collected for physical analysis in 1985 were also analyzed for chemical constituents using the saturated paste extract method. The purpose of collecting these samples was to initially characterize the site with respect to soil chemistry. Note that this is a different sampling plan than what is used for measuring annual changes in soil salinity (refer to Section 3.3.5). Data from chemical analysis can be found in Appendix D.

The north parcel was observed to exhibit significantly (α=0.05) different pH values (Figure 4.5) than the south parcel for all depths except for the 45-90 cm depth interval, with the difference being the largest at depths greater than 1 m. Average pH values for the entire 0-180 cm range were 7.8 for the south parcel and 8.0 for the north parcel. With respect to both parcels, the overall trend is that the profile was more basic for samples collected in the mid-depths than those collected near the surface or at depth.

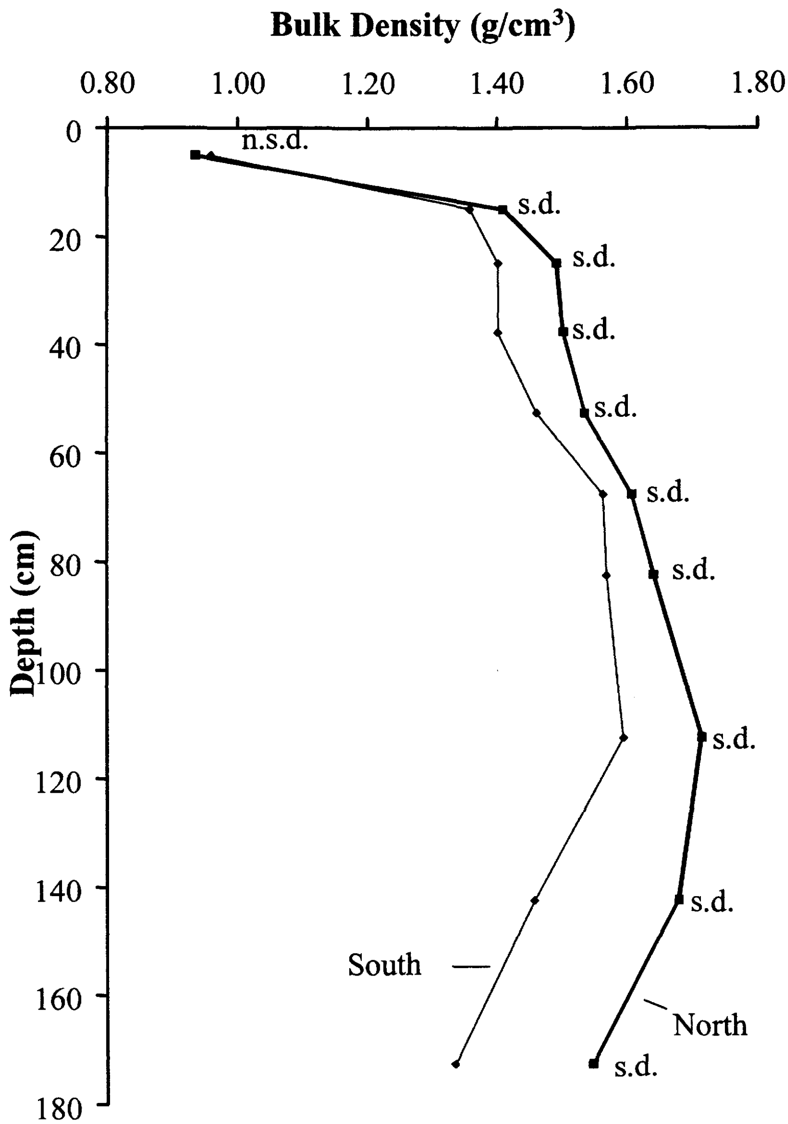
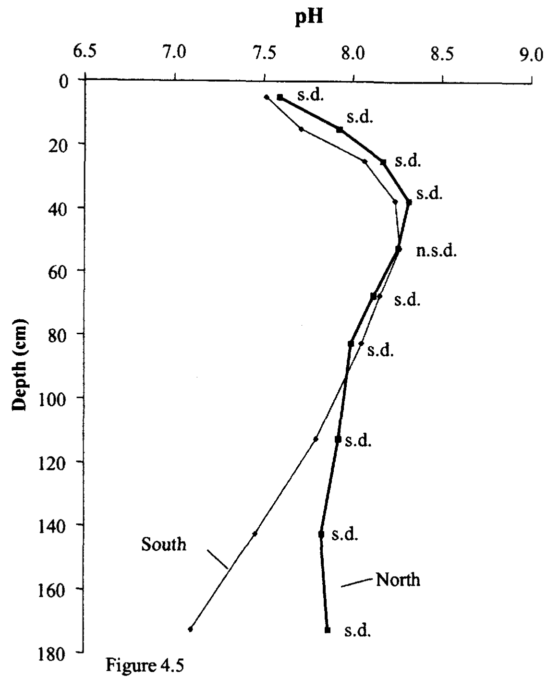


Figure 4.4: Soil bulk density - depth profile.
Note: Abbreviations s.d. and n.s.d. following data points indicate whether or not the two parcels are significantly different (t-test, $\alpha = 0.05$).

The average EC_e depth profile (Figure 4.6) was similar for the south and north parcels with relatively high concentrations near the surface, maximum values occurring at 30-45 cm, followed by a decrease in concentrations with depth. One interesting feature is that the two parcels started to deviate below 120 cm, with the south parcel exhibiting significantly (α=0.05) different EC_e values. The mean EC_e of the entire profile (0-180 cm) was 9.8 dS/m for the south parcel and 9.4 dS/m for the north parcel.

Sulphate, and Na^+ ions were found in the highest relative concentrations of all of the ions tested. Mg^{2+} and Ca^{2+} also existed in high quantities relative to observed minor concentrations of Cl^-, and K^+. Ionic concentrations, averaged for the entire 180 cm depth, are presented in Table 4.3. Although carbonates were not tested for, a simple cation/anion balance would suggest that HCO_3 should have existed in minor concentrations of around 20 meq/l (south) and 26 meq/l (north). As a result of the high Na^+ content, the SAR of the soil extracts were also quite high. SAR values (Figure 4.7) are somewhat higher for the north parcel, yet only differ significantly ($\alpha = 0.05$) at three depths. Sodium adsorption ratio averages for the profile (0-180 cm) were 18.0 for the south parcel and 19.4 for the north parcel.



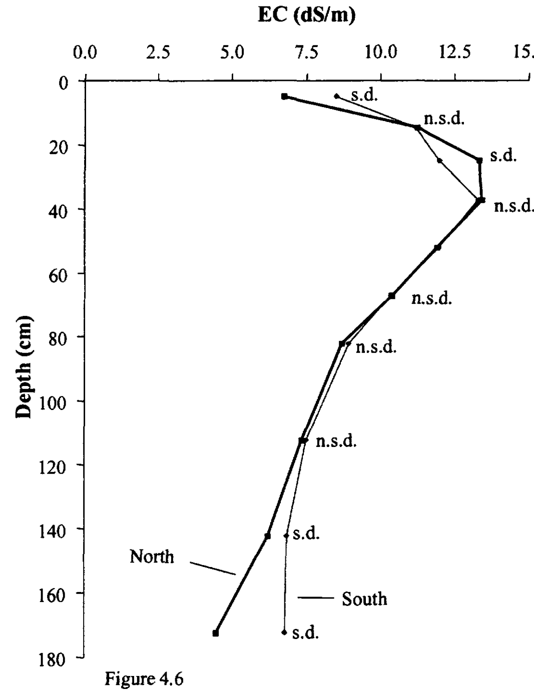


Figure 4.5: Saturated soil paste extract pH - depth profile, averaged from selected locations.

Figure 4.6: Saturated soil paste extract Electrical Conductivity (EC_e) - depth profile, averaged from selected locations.

Note: Abbreviations s.d. and n.s.d. following data points indicate whether or not the two parcels are significantly different (t-test, $\alpha = 0.05$).

Table 4.3: Average ionic concentrations (0-180 cm depth) of saturated paste extracts.

Ion	South Parcel (meq/l)	North Parcel (meq/l)
Cl^-	1.3	1.9
SO_4^{2-}	161.9	133.3
Ca^{2+}	19.1	17.0
Mg^{2+}	49.2	33.9
Na^+	114.1	108.7
K^+	1.2	1.3

Note: Number of samples used to calculate average values were 363 (south) and 251 (north).

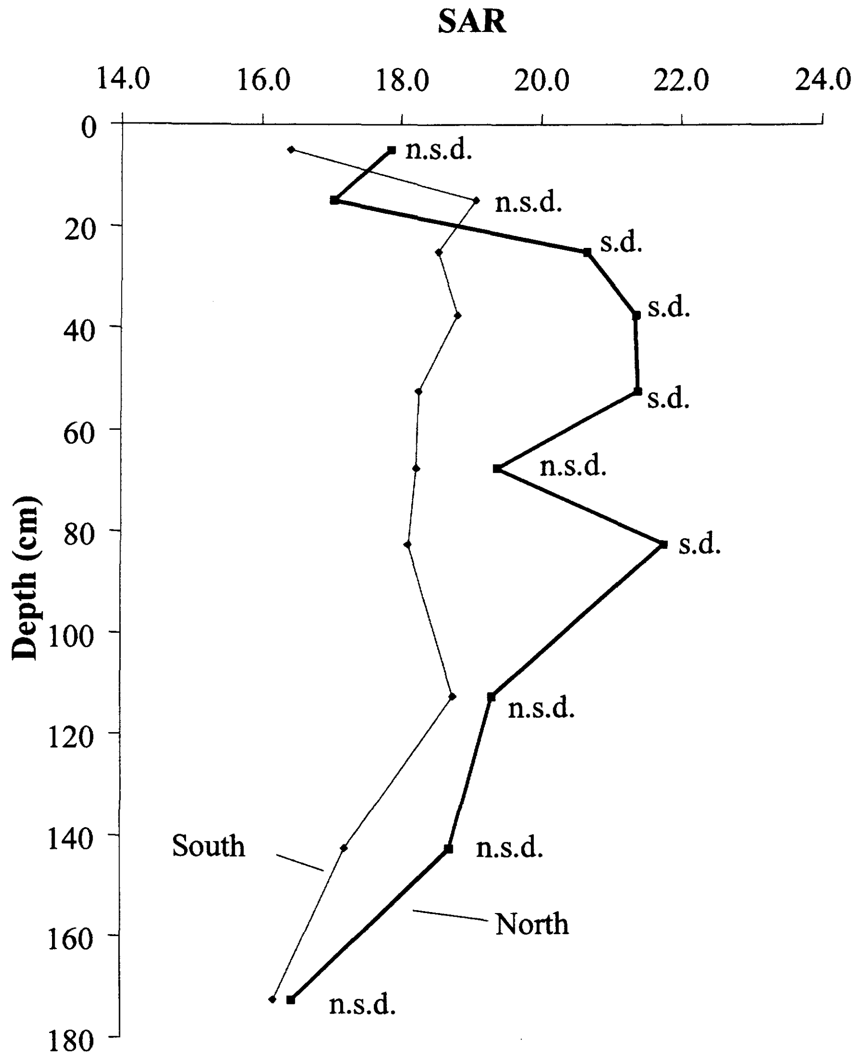


Figure 4.7: Saturated soil paste extract sodium absorption ratio (SAR) - depth profile, averaged from selected locations.
Note: Abbreviations s.d. and n.s.d. following data points indicate whether or not the two parcels are significantly different (t-test, $\alpha = 0.05$).

4.3 Seasonal and Continuous Site Monitoring

4.3.1 Hydrology

a) Water table position

Mean water table positions for each parcel are presented in Figure 4.8. The traditional drainage system was installed in the south parcel during September 1990 and the experimental drainage system was installed in the north parcel during September

1997. From this figure, it is observed that the frequency and direction of the water table fluctuations were very similar for each parcel throughout the entire study period. However the magnitude of these fluctuations was very different, particularly in the post-drainage period of the south parcel (traditional drain system). The experimental drainage system was operated periodically during 1998 and 1999 and consequently it is difficult to see the specific operation details at the time scale presented in Figure 4.8.

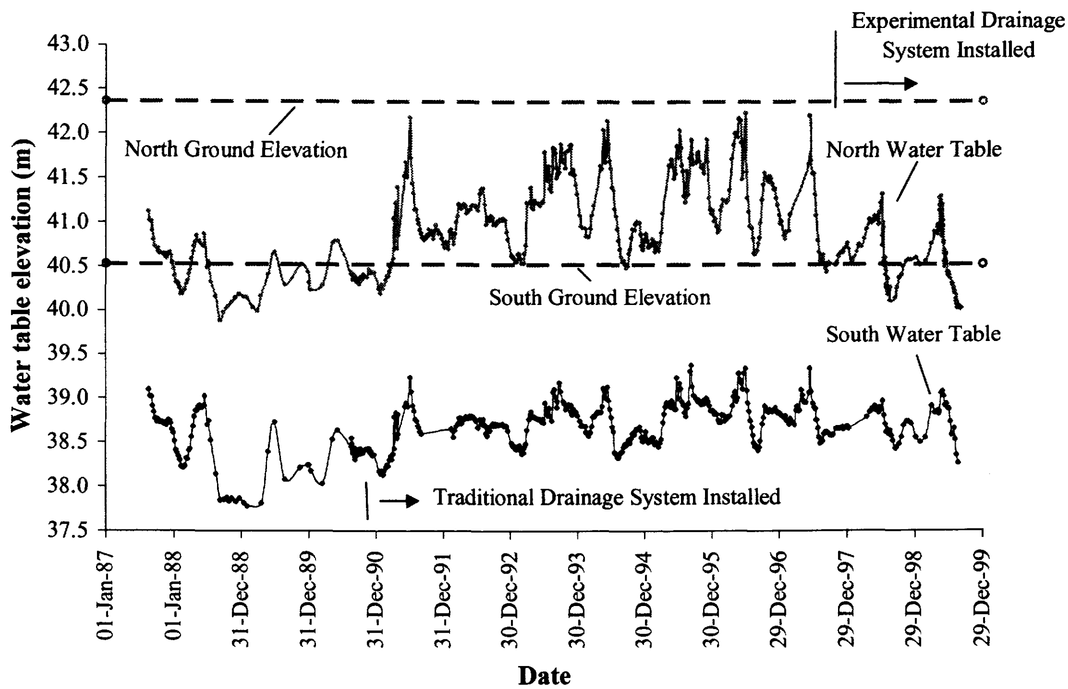


Figure 4.8: Average water table elevations for south (traditional drainage treatment) and north (experimental drainage treatment) parcels.

More detailed water table information can be found in Figures 4.9 through 4.14 where mean water table elevations for each parcel, and wells 5516 and 5046 are plotted on a yearly basis for years 1997 to 1999. From Figure 3.2, it is clearly seen that the locations of wells 5516 and 5046 are not directly in the center of the group of averaged wells. As a result, when a sloped water table occurred, the depth to water in each of these wells was different than the calculated average for each parcel.

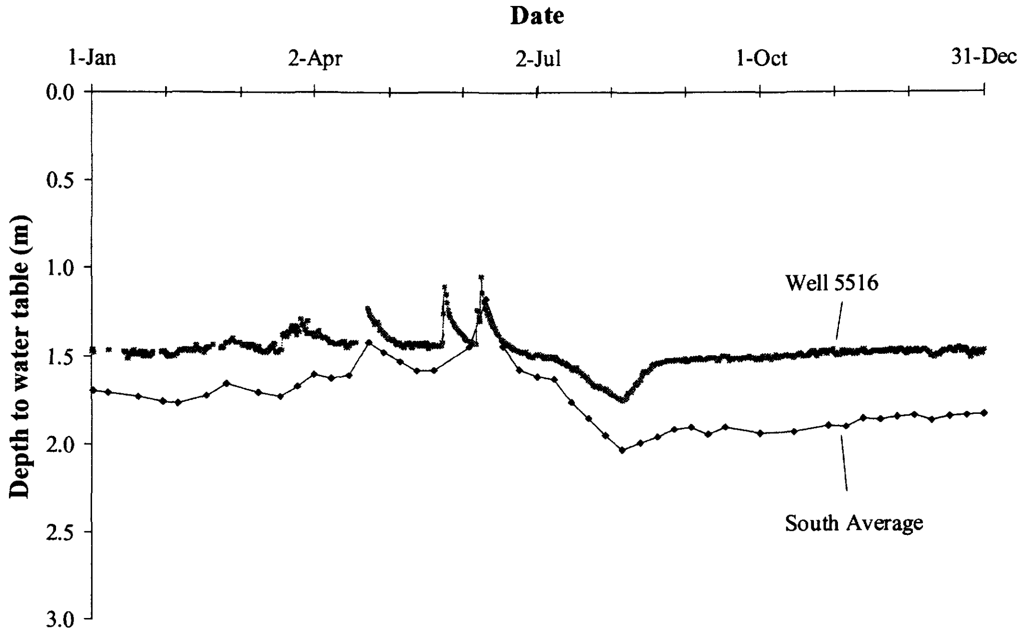


Figure 4.9: 1997 south parcel (traditional) water table depth.

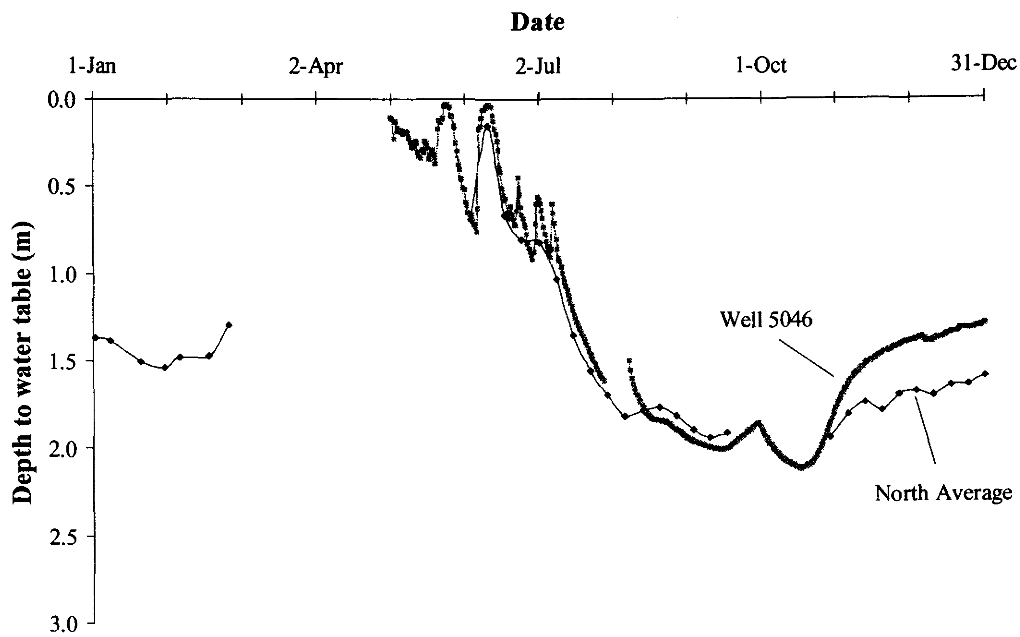


Figure 4.10: 1997 north parcel (experimental) water table depth.

During March to June of 1997 (Figure 4.10) the north parcel experienced water tables right up to the soil surface. Consequently a number of wells were frozen, explaining the lack of measurements reported prior to the beginning of May. On the contrary, the water tables in the south parcel (Figure 4.9) showed a minimum depth of approximately 1.25 m from the soil surface in 1997.

The hydrograph of the south parcel during 1998 (Figure 4.11) is quite flat, only showing a small (< 10 cm) rise in the water table during June. The north parcel however, experienced near surface water table (observed in well 5046) towards the end of June, prior to operation of the experimental drainage system. During drainage, the water table was reduced to below 2 m in the group of average wells and in well 5046. Towards the end of the year, following the drainage operations, the water table in the north parcel rose to approximately 1.8 m from the surface for the group of averaged wells and to 1.5 m for well 5046.

The depth to water hydrographs for the year of 1999 show similar results as those observed in 1998. The south parcel (Figure 4.13) hydrograph showed slight short term increases (> 30 cm) in water table depth during the middle of March and the middle of May. The hydrograph of the north parcel (Figure 4.14) responded in a different matter in that the water level observed in well 5046 was raised from 1.5 m below the ground surface at the beginning of the year to around 30 cm from the surface by the middle of May. During the drainage operations of the experimental system, the water levels in the group of averaged wells and in well 5046 dropped to below 2 m.

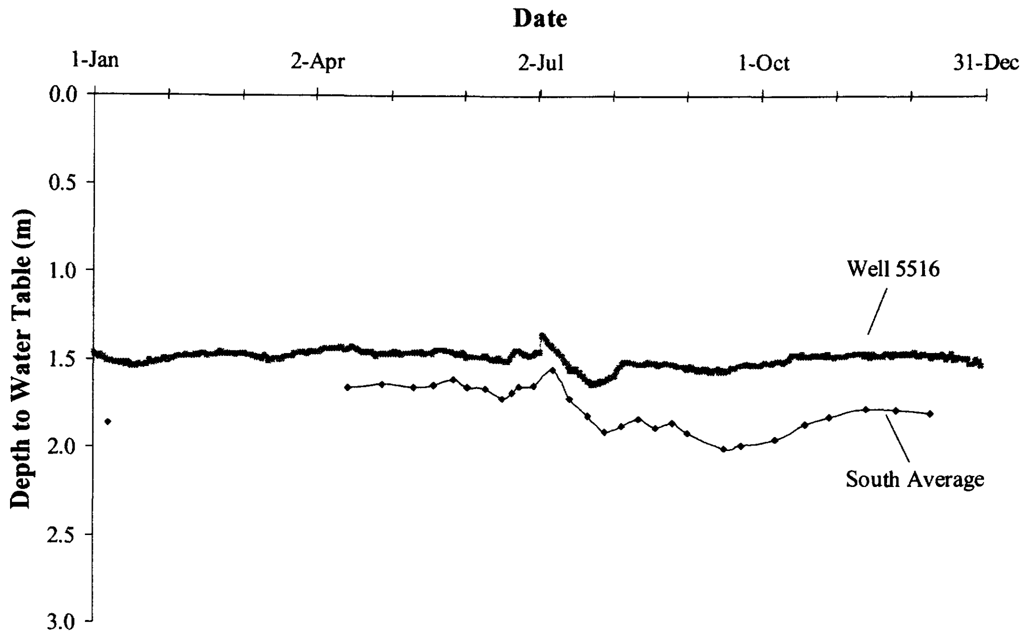


Figure 4.11: 1998 south parcel (traditional) water table depth.

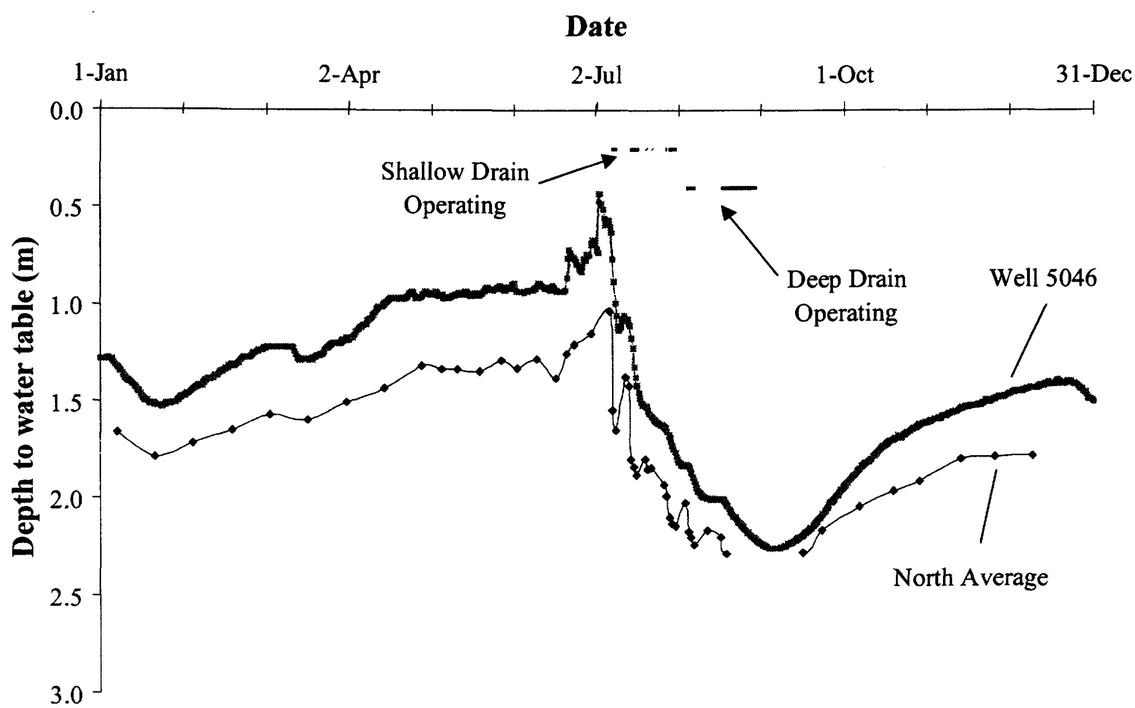


Figure 4.12: 1998 north parcel (experimental) water table depth.
Note: horizontal bars indicate the period of time that the experimental drainage system was opened.

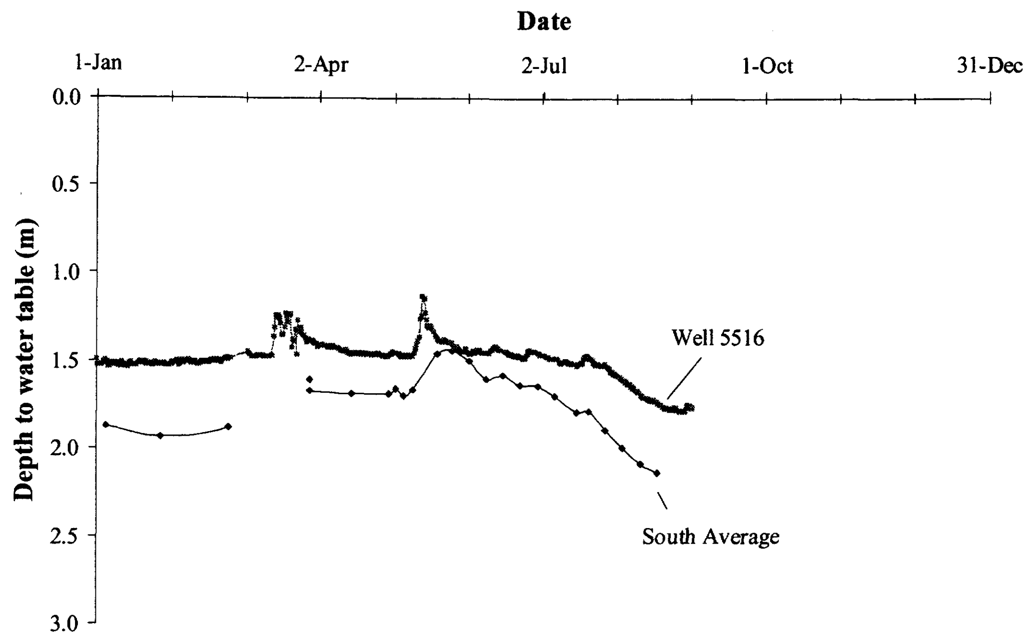


Figure 4.13: 1999 south parcel (traditional) water table depth.

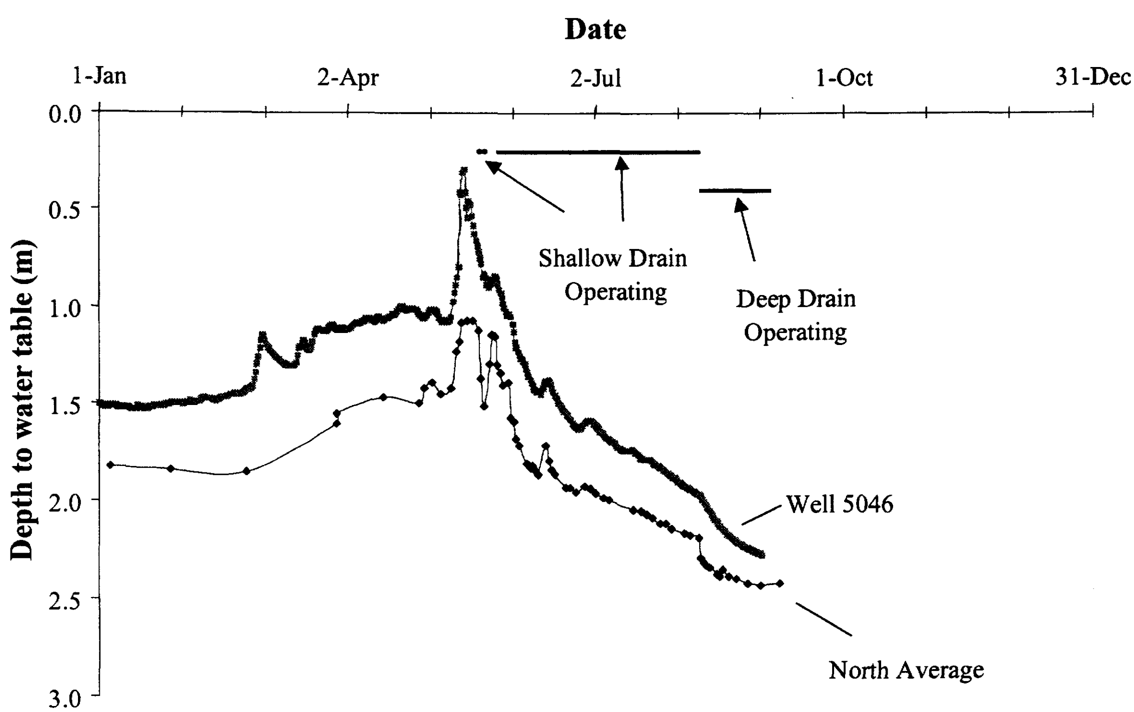


Figure 4.14: 1999 north parcel (experimental) water table depth.
Note: horizontal bars indicate the period of time that the experimental drainage system was opened.

b) Soil moisture

Average soil moisture measurements, obtained during 1998, are shown in Figures 4.15 and 4.16 for the south and north parcels respectively. The dates chosen for measurement corresponded to drainage activities in the north parcel: May 8th was pre-drainage, July 8th marked the start of drainage, and August 26th occurred during a later stage of drainage. Moisture measurements were also obtained for June 5th, July 8th, and August 12th. This information can be found in Appendix E.

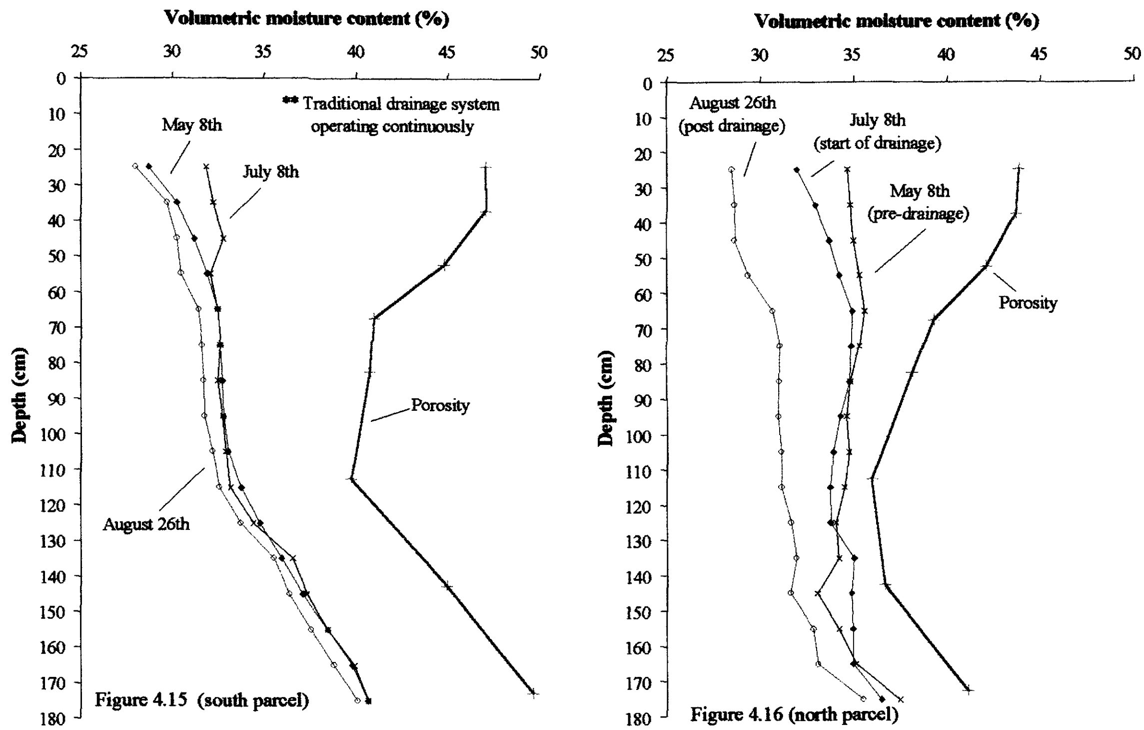


Figure 4.15: Average moisture content of south parcel (1998)

Figure 4.16: Average moisture content of north parcel (1998)

Average soil porosity values, also presented in Figures 4.15 and 4.16 were calculated from the bulk density information presented in Section 4.2.1, assuming a soil particle density of 2.65 kg/m^3. Moisture contents at field capacity (0.3 atm.) for these soils, based on average soil texture (30-180 cm), are estimated to range between 0.40–0.45 m^3/m^3 (de Jong 1967).

With respect to Figure 4.15, the moisture content of the south parcel stayed nearly constant with time. Rainfall events were seen to have increased the soil moisture in depths down to 55 cm as observed on July 8th. During the period of time between June 5th and July 8th the on-site precipitation guage had received 92 mm of rain. For the last measurement date, the moisture content vs. depth profile shape was very similar to that of the initial measurement date.

In the north parcel (Figure 4.16), the May 8th measurement date showed a much more moist profile than that observed in the south parcel. By the August 26th measurement, following drainage, the moisture content was much lower than initial dates throughout the entire profile and more closely resembled the profile shape of the south parcel.

c) Drainage effluent

*i. **Traditional drainage system (south parcel)***

Discharge rates from the traditional drain system in the south parcel are presented in Figure 4.17 along with daily precipitation amounts as measured at the SPARC weather station. Years 1997 through 1999 are also presented in Figures 4.18 through 4.20 to provide greater detail about flow processes in recent years. From these graphs, the relationship between drainage flow rate and precipitation can be verified. Generally, in most years winter flow was quite low (less than 5 ℓ/min) followed by a marked increase after snowmelt. Peak flows (ranging from less than 10 ℓ/min to over 70 ℓ/min) generally occurred in summer due to large precipitation events. Notice that in years not exhibiting large precipitation events, peak flows were generally quite small (such is the case in 1992 and 1998). The relationship between flow rates and precipitation is most valid during the earlier summer months when soils are more wet and evapotranspiration does not account for a large portion of the precipitation. For example in 1999, (Figure 4.20) the peak flow (19.2 ℓ/min) occurred in May, and despite heavy precipitation throughout June and July, only smaller flow rates of less than 10 ℓ/min were observed. In many years, flow periodically ceased during the typically dry months of July and August.

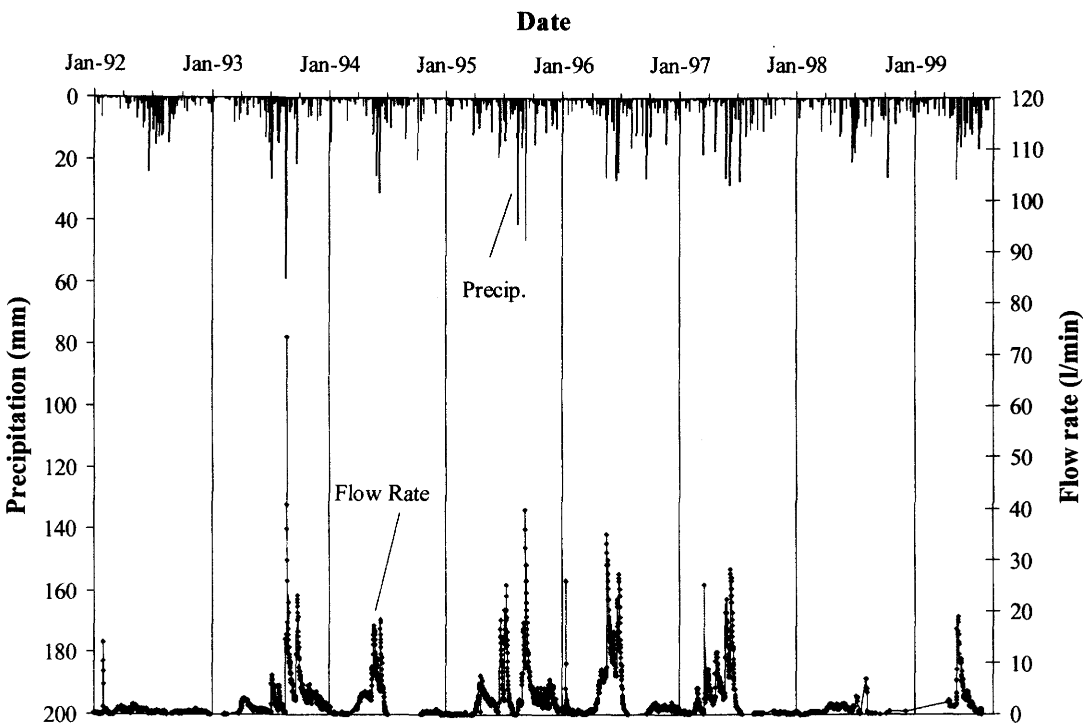


Figure 4.17: Traditional drainage system discharge rate and daily precipitation (January 1992 – September 1999).

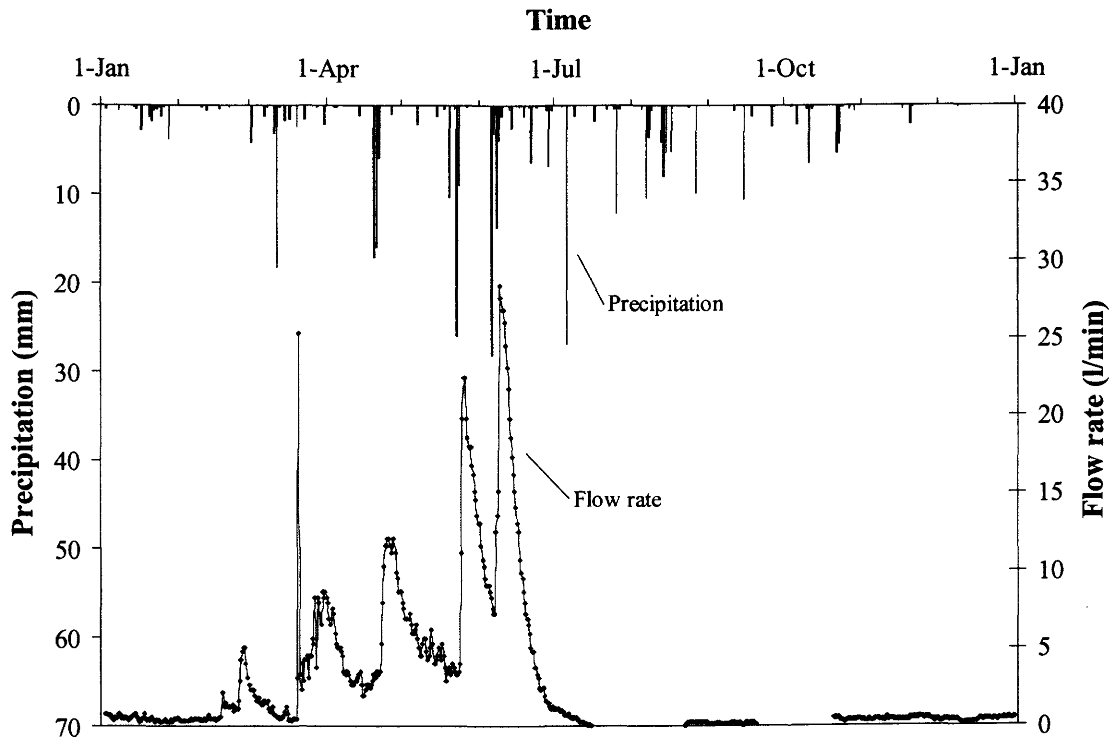


Figure 4.18: 1997 traditional drainage system discharge and daily precipitation.

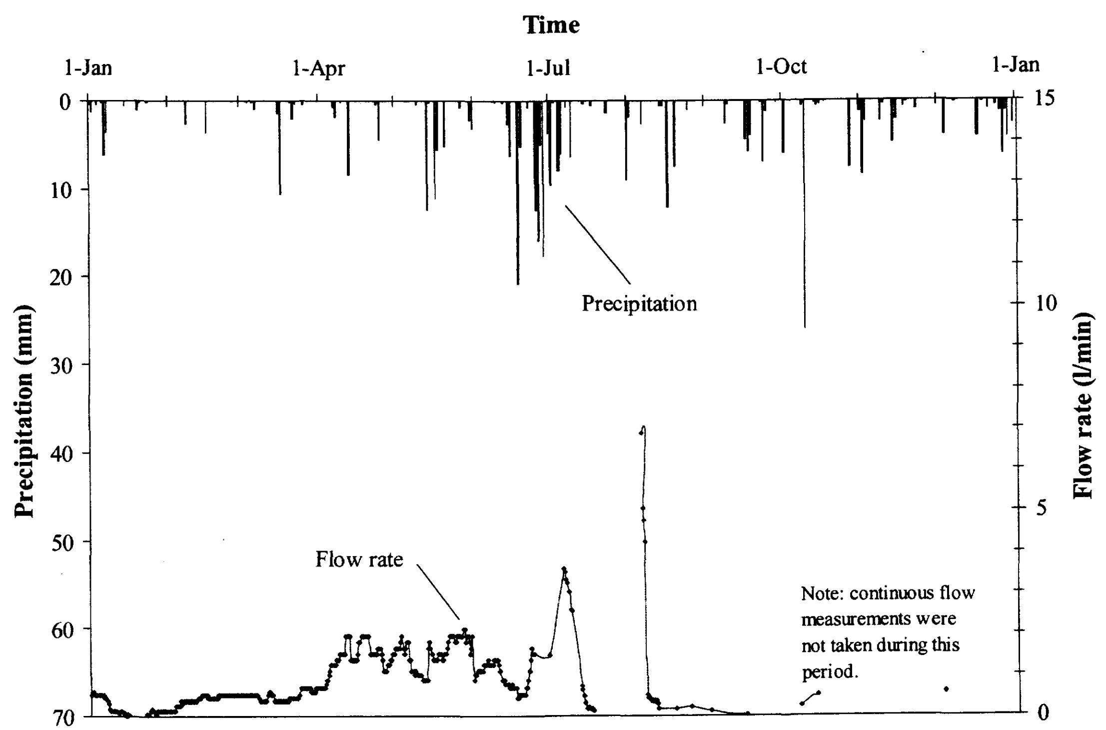


Figure 4.19: 1998 traditional drainage system discharge and daily precipitation.

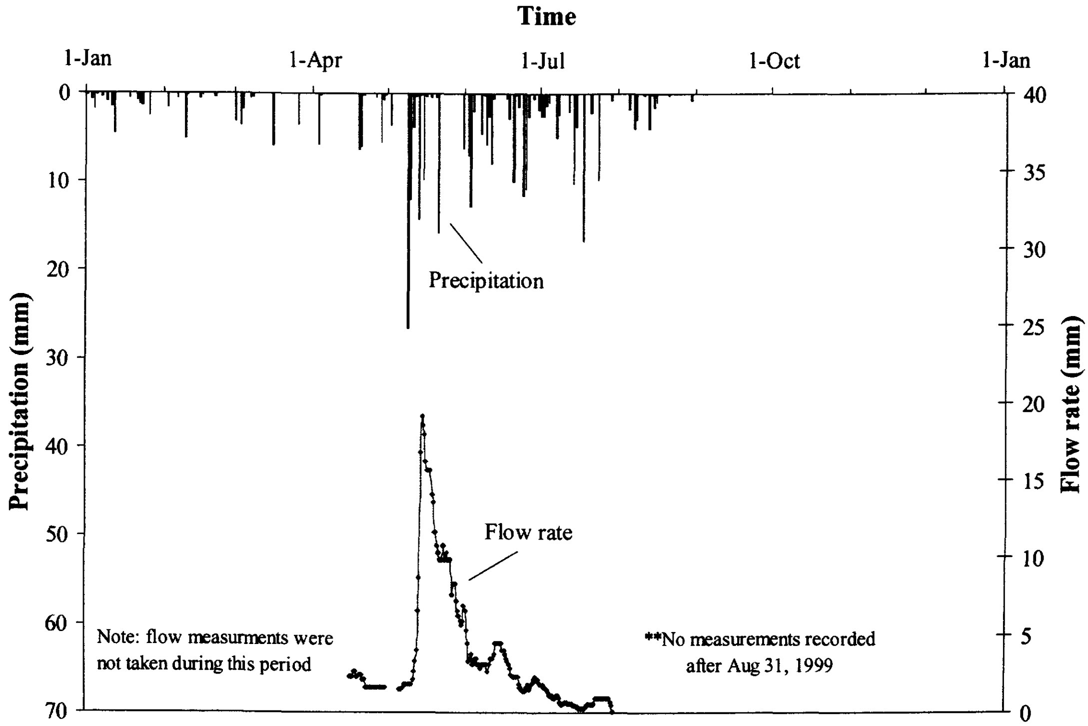


Figure 4.20: 1999 traditional drainage system discharge and daily precipitation.

*ii. **Experimental drainage system (north parcel)***

Figure 4.21 shows the experimental system flow rate and the depth to water in the drainage well during 1998. The depth to water for the drainage well was included, because it gives a clear picture of the hydraulics of the system. Note that this well has a very strong hydrologic connection with the drainage system as they are separated only by gravel fill. During 1998 the drain was operated according to the demand of the irrigation system, as reflected by the irregular operation schedule. Table 4.4 gives the dates of each drainage operation and reveals the amount of water released from the system each time. Technical difficulties prevented measurement of some of the discharge from the deep option so consequently the values in late August of each year are not reported in Table 4.4.

Table 4.4: Experimental drainage system operation schedule and discharge volumes.

Start Date/Time	End Date/Time	Volume (m^3)	System
Jul 7, 1998 13:30	Jul 9, 1998 16:30	57.1	Shallow
Jul 14, 1998 14:30	Jul 17, 1998 16:30	55.9	
Jul 20, 1998 8:30	Jul 20, 1998 16:00	8.3	
Jul 22, 1998 10:00	Jul 22, 1998 15:00	5.3	
Jul 27,1998 8:30	Jul 27, 1998 16:30	9.9	
Jul 28, 1998 14:00	Jul 31, 1998 15:30	30.0	
Aug 4, 1998 8:00	Aug 7, 1998 15:30	40.1	Deep
Aug 17, 1998 8:00	Aug 28, 1998	n.a.	
May 20, 1999 14:00	May 22, 1999 14:00	24.1	Shallow
May 26, 1999 12:00	Aug 9, 1999 13:00	556.8	
Aug 9, 1999 13:00	Aug 19, 199915:30	43.8	Deep
Aug 19, 199915:30	Sep 4, 1999	n.a.	

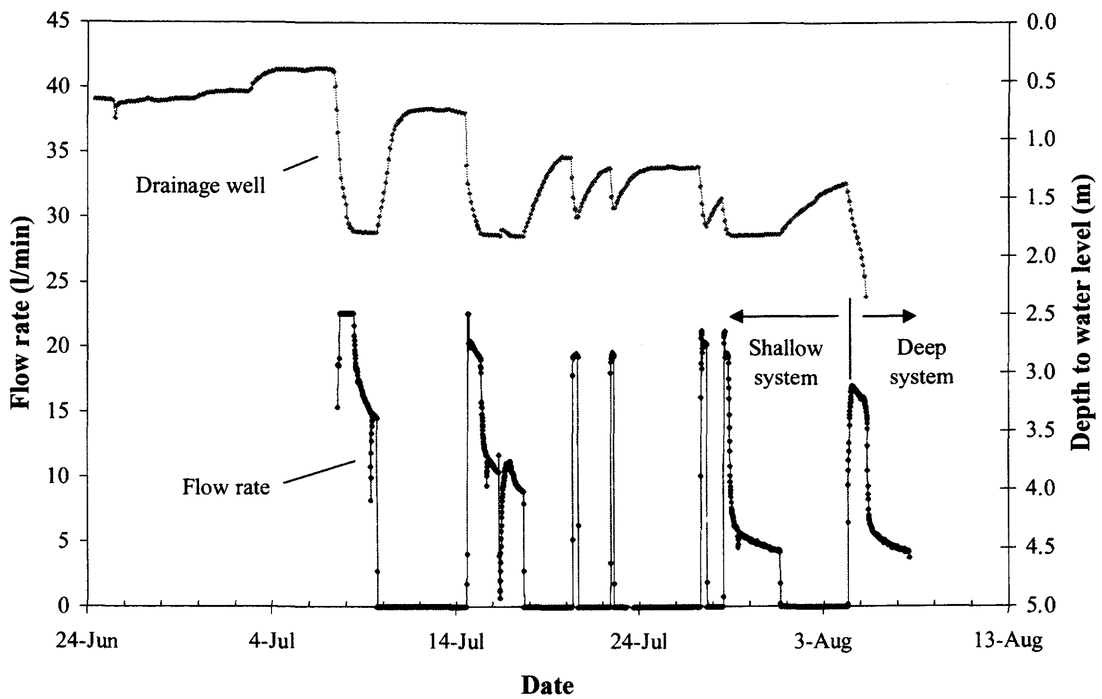


Figure 4.21: Experimental drainage system flow rate and depth to water in drainage well (Jun. 24 – Aug 13, 1998).

The response of the experimental system to the first two drainage activities in 1998 can be better seen in Figure 4.22, essentially a magnified section of Figure 4.21.

When the drain was first opened (July 7th), a maximum flow rate of approximately 22 l/min was observed. By July 8th, when the water within the well dropped to approximately 1.8 m below the surface (shallow drain depth), the drain lines stopped flowing full, and the flow rate through the system dropped rapidly. When the drain line was closed again (July 9th) the water level in the well quickly rose again. A similar response was noticed during the second drain operation (July 14th to July 17th).

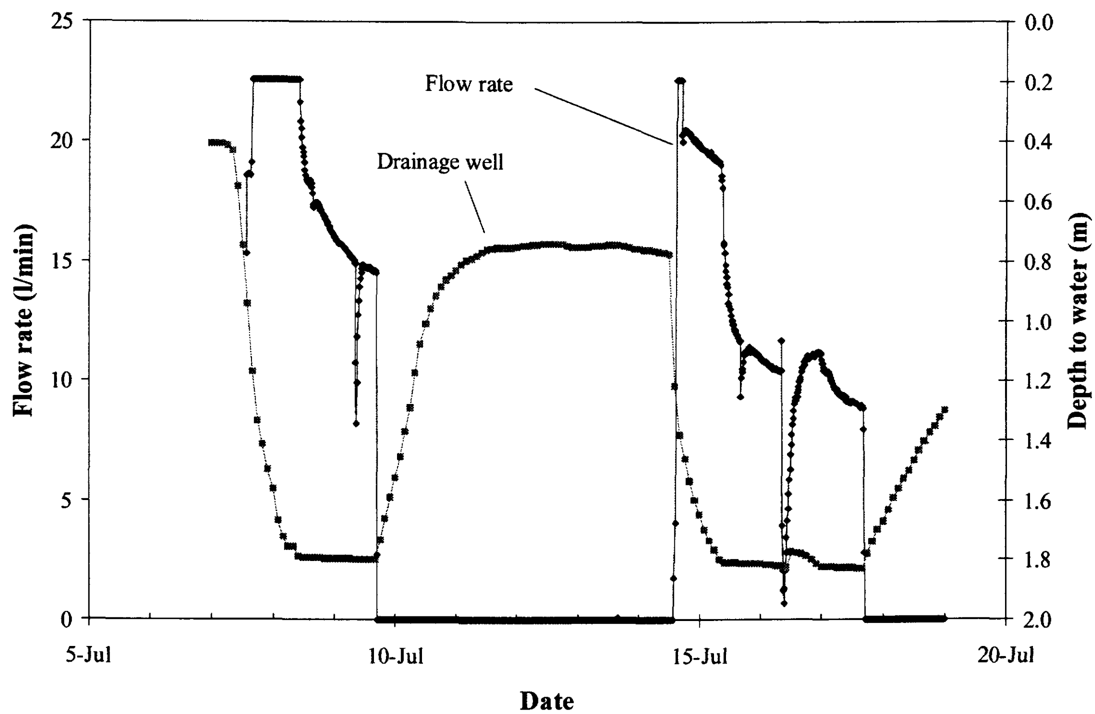


Figure 4.22: Experimental drainage system flow rate and depth to water in drainage well (Jul. 5 – Jul. 20, 1998).

The effect of flow rate and precipitation on water table elevations within the north parcel during 1998 can be seen in Figure 4.23. Well readings used to calculate the average were taken on a concentrated schedule surrounding each drain operation, while well 5046 was continuously recorded automatically. From inspection of Figure 4.23, both curves indicate that the water table responded to drainage activities: dropping when the drain was opened and recovering somewhat when the drain was closed. Water level recovery is only apparent on Figure 4.23 when the depth to water table was considerably less than the average depth of the shallow system (July 8^{th} to July 15^{th}).

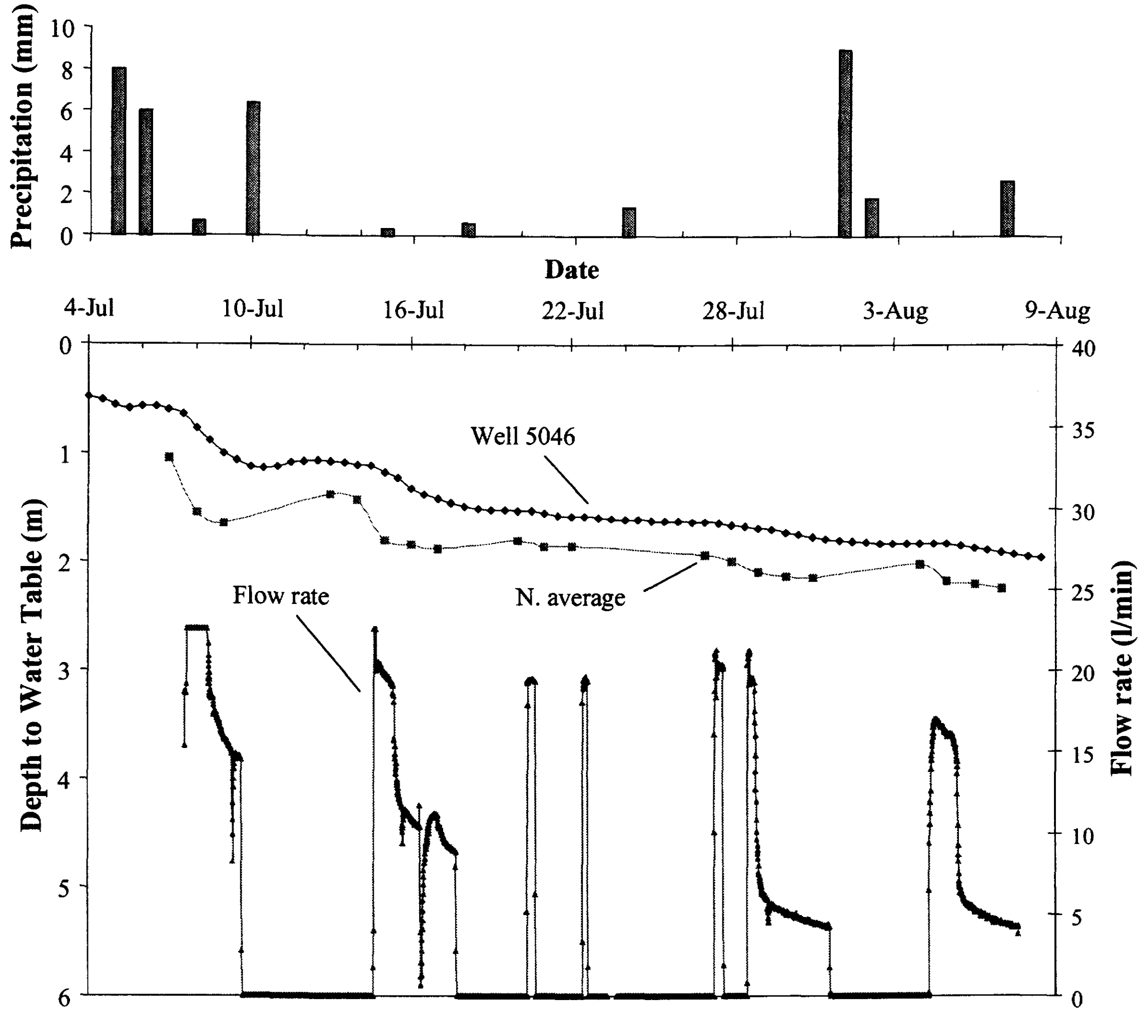


Figure 4.23: Effect of experimental drainage system flow rate and precipitation amounts on north parcel water table depth (Jul 4 – Aug 9, 1998).

In 1999, a different operating strategy was chosen for the experimental system. For this season, the system was left open as continuously as possible. The drain system was coupled directly to the trickle irrigation system allowing the irrigation system to limit the flow from the parcel. On July 22nd, the system was disconnected from the irrigation system and was directed to a settling basin located to the southeast of the study site. This was done in order to facilitate field activities in the area that the irrigation line was placed.

Figure 4.24 shows the relationship between the discharge rate for the drain and the water level in the drainage well for 1999. On a couple of occasions, large differences in flow rates occurred, because the number of emitters providing water was temporarily changed. Such is the case at points 'a' and 'b' in Figure 4.24, where the effect of varying flow rate on the drainage system can be seen quite clearly. Here, the rate that the water level in the drainage well was dropping was decreased on each occasion.

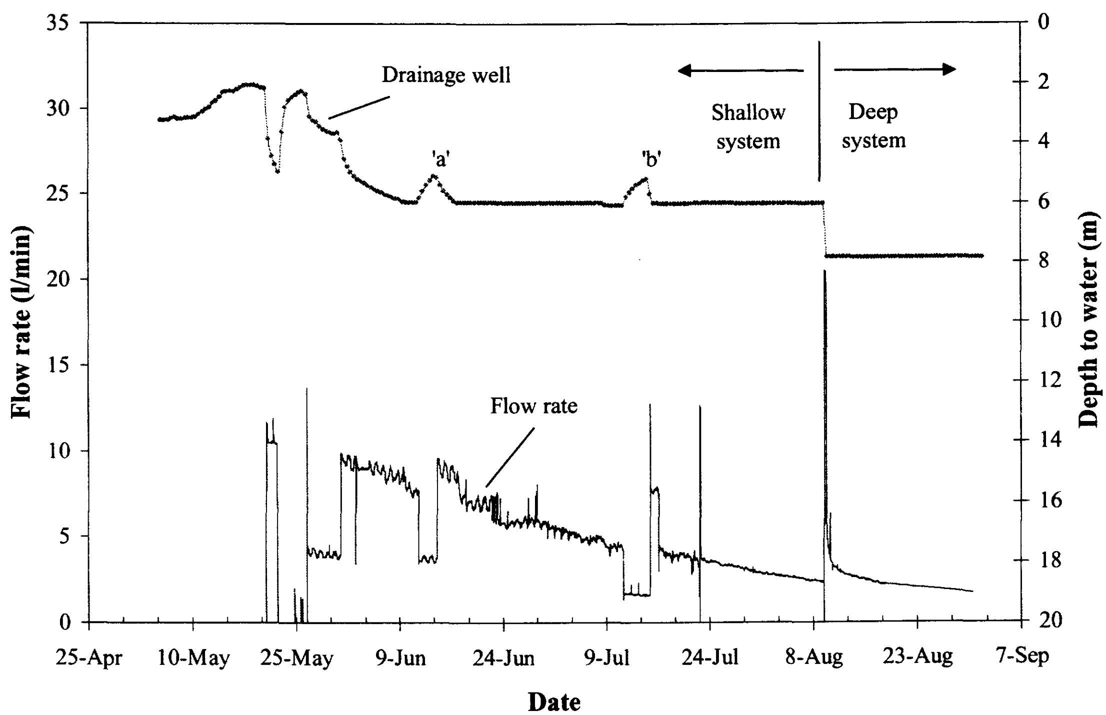


Figure 4.24: Experimental system flow rate and depth to water in drainage well (Apr. 25 – Sep. 7, 1999).
Note: see text for explanation of points 'a' and 'b'.

On August 9th, the deep drainage option was opened and the water level within the drainage well was observed to rapidly drop to the depth of the deeper system (Figure 4.24). An immediate increase in flow rate was observed, but within a day the flow had returned to the rate experienced immediately prior to opening the deep system.

The response of the water table in the north parcel to the drainage activities of 1999 can be seen in Figure 4.25, where the averaged group of wells and well 5046 are shown. Similar to the trend observed in Figure 4.24, the effect of varying flow rates was noticed in well 5046 and the group of averaged wells. An interesting note is that the water level dropped only a small distance due to the incremental opening of the deep option.

4.3.2 Chemistry

a) Soil chemistry

Soil samples at the site have been taken annually, usually during September or October since 1985. Figures 4.26a and 4.26b compare EC_e values obtained at each 15-cm depth interval from saturated paste extracts in each parcel for years 1988 through 1999.

Prior to installation of the traditional drainage system (Figure 4.26a), the EC_e values of the south parcel were quite variable with respect to depth. Following drainage, EC_e reductions of the 0-15, 15-30, 30-45, and 45-60 cm depths were observed. An increase in the EC_e of the 60-75 and 75-90 cm depths occurred during the same period. For all years following drainage, the EC_e of the 0-15 cm depth interval exhibited the lowest salinity levels of all the depths sampled, remaining below 10 dS/m. Based on the data and analysis used for this study, by October 1999, the average EC_e of the 0-90 cm profile had decreased by 0.9 dS/m with respect to 1990 levels.

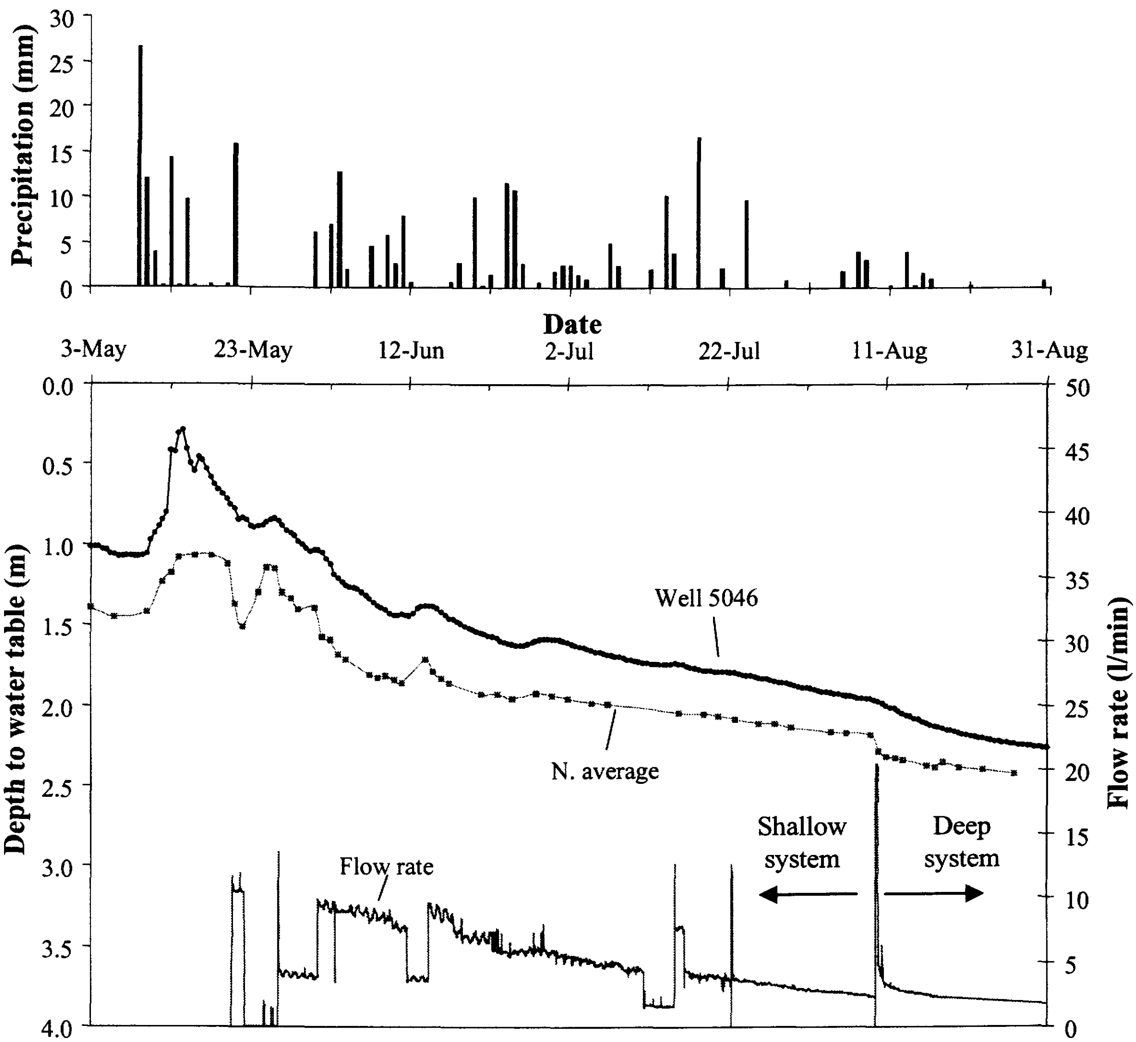


Figure 4.25: Effect of experimental system flow rate and precipitation on north parcel water table depths (May 3 – Aug. 31, 1999).

The EC_e of the north parcel (Figure 4.26b) generally tended to decrease with depth, throughout all of the years presented. The 0-15 cm interval was the most variable layer, ranging by over 13 dS/m during the study period. By October 1999, following installation of the experimental drainage system, the EC_e decreased by 4.8 dS/m (with respect to 1997 conditions) in the 0-15 cm depth interval. During the same period an increase in EC_e was observed in all lower depth intervals. Overall, there was an increase of 1.7 dS/m for the entire 0-90 cm profile.

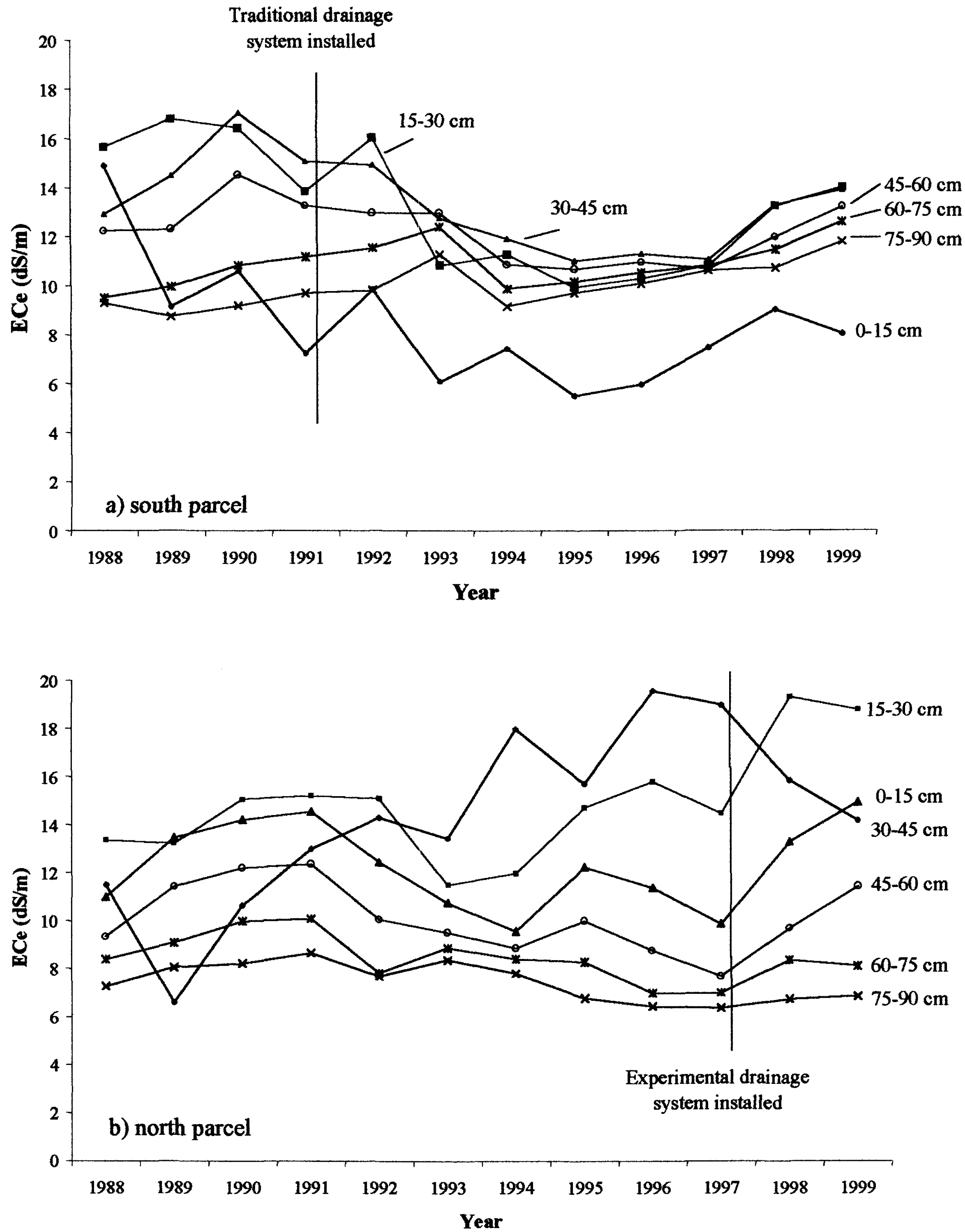


Figure 4.26: Saturated paste extract EC_e (a) south parcel, (b) north parcel.
Note: Each point is a calculated average of the sampling locations used for this study.

Prior to drainage, crop growth was not possible in either parcel. After installation of the traditional drainage system, a crop has been produced in the south parcel every year since 1991. Similarly, after installation of the experimental drainage system, a crop was produced in the north parcel during 1999. Although quantitative measurements of crop yield are not available, based on visual estimates and farmer feedback, crop growth increases were accepted as being large enough that most landowners would be satisfied.

b) Water chemistry

i. Monitoring wells

Chemical analysis results for water samples obtained biannually from monitoring wells are presented in Figures 4.27a and 4.27b. Of the ions measured, SO_4^{2-}, Na^+, Mg^{2+}, and Ca^{2+} were found in the highest proportions in both parcels. Overall, ion concentrations were much higher in the south parcel than the north parcel. The south parcel exhibited a slightly different composition than the north parcel, as the SO_4^{2-} concentrations were much higher than Na^+, whereas they existed in similar amounts in the north parcel. Also of interest is how specific sampling dates indicated drastically increased concentrations, as shown by the sampling dates of spring 1990 and spring 1991 (north parcel) and spring 1997 (south parcel). These anomalies will be discussed in later chapters.

Acidity (pH), EC, and SAR are presented in Figures 4.28 through 4.30. The pH of the two parcels did not differ much, and for the most part tended to follow a similar pattern in each parcel. The EC (Figure 4.29) of the water in the south parcel exhibited notably higher EC values in every year, except for the spring of 1991. Trend analysis indicated that there was a significant increase (α=0.05) in the average EC of the monitoring wells of both parcels over the study period. The SAR (Figure 4.30) of the water was also higher for the south parcel in most years. It should be noted that monitoring wells were only sampled on one specific date in each season and are subject to periodic variations in water quality.

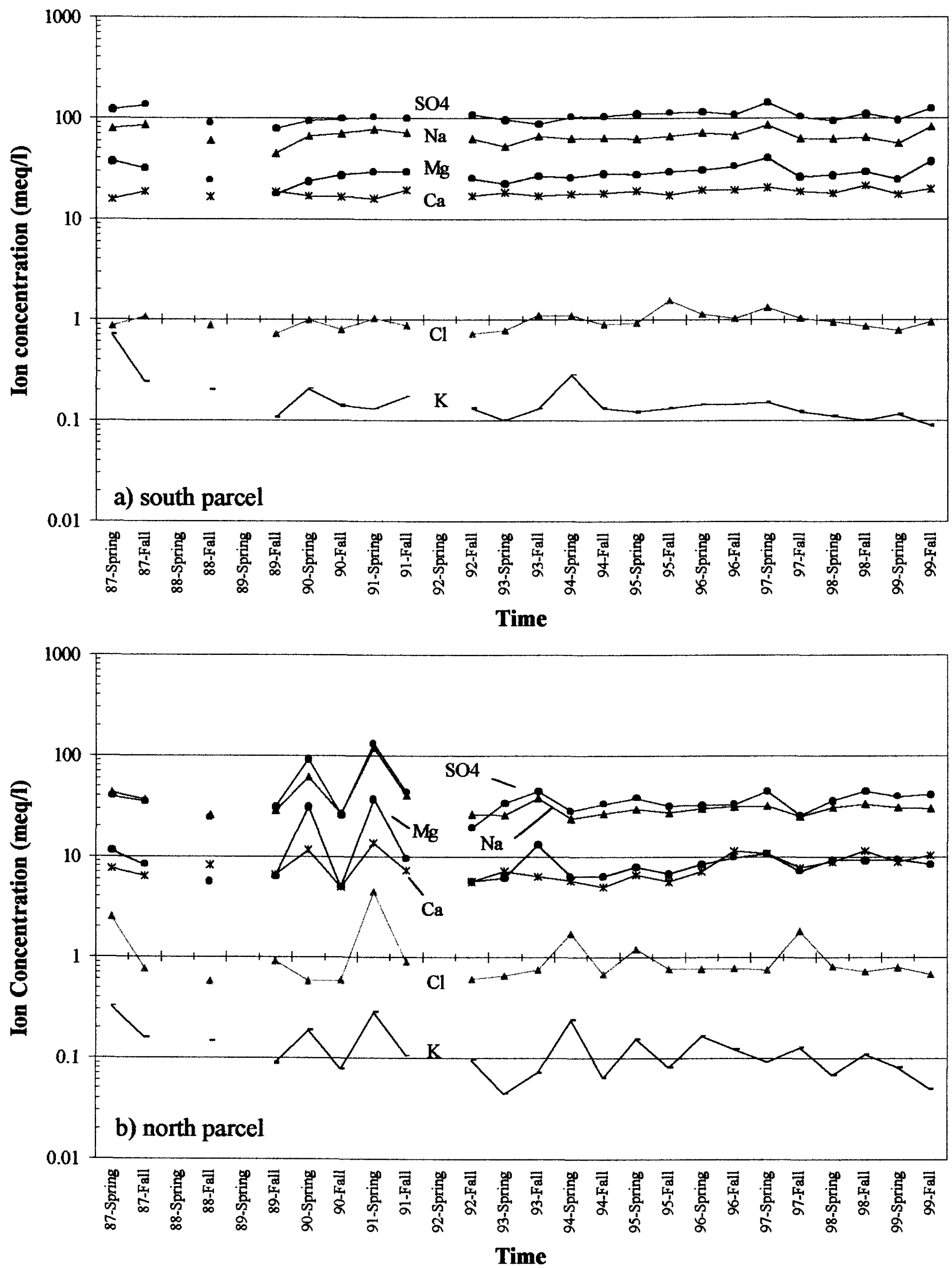


Figure 4.27: Monitoring well ion concentration: (a) south parcel, (b) north parcel.

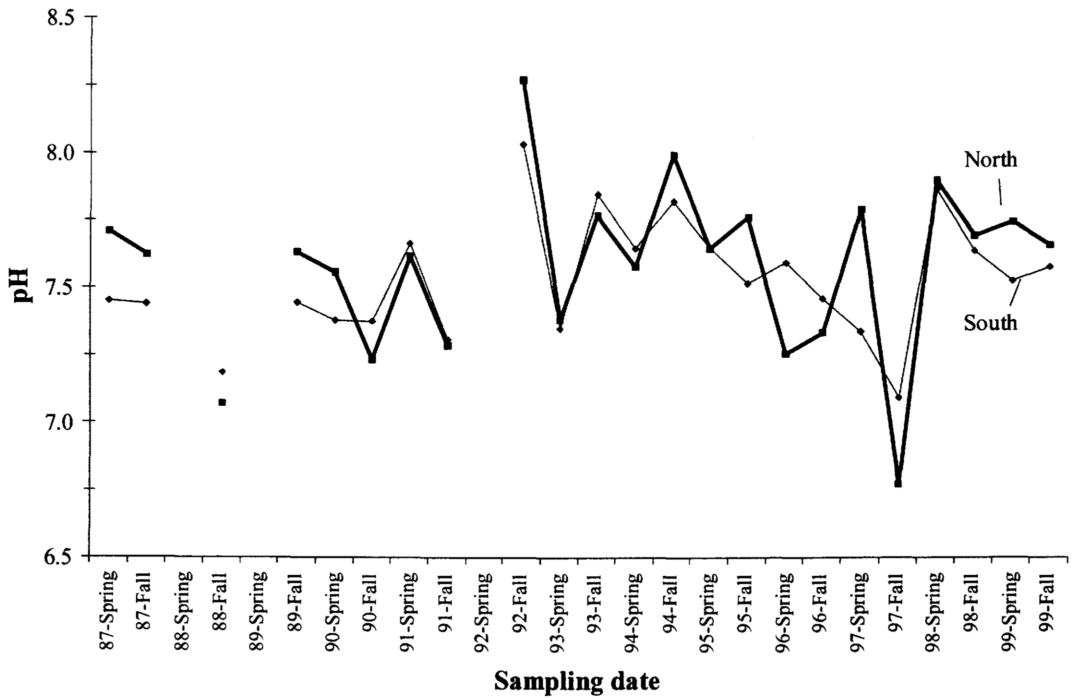


Figure 4.28: Acidity (pH) of water sampled from monitoring wells.

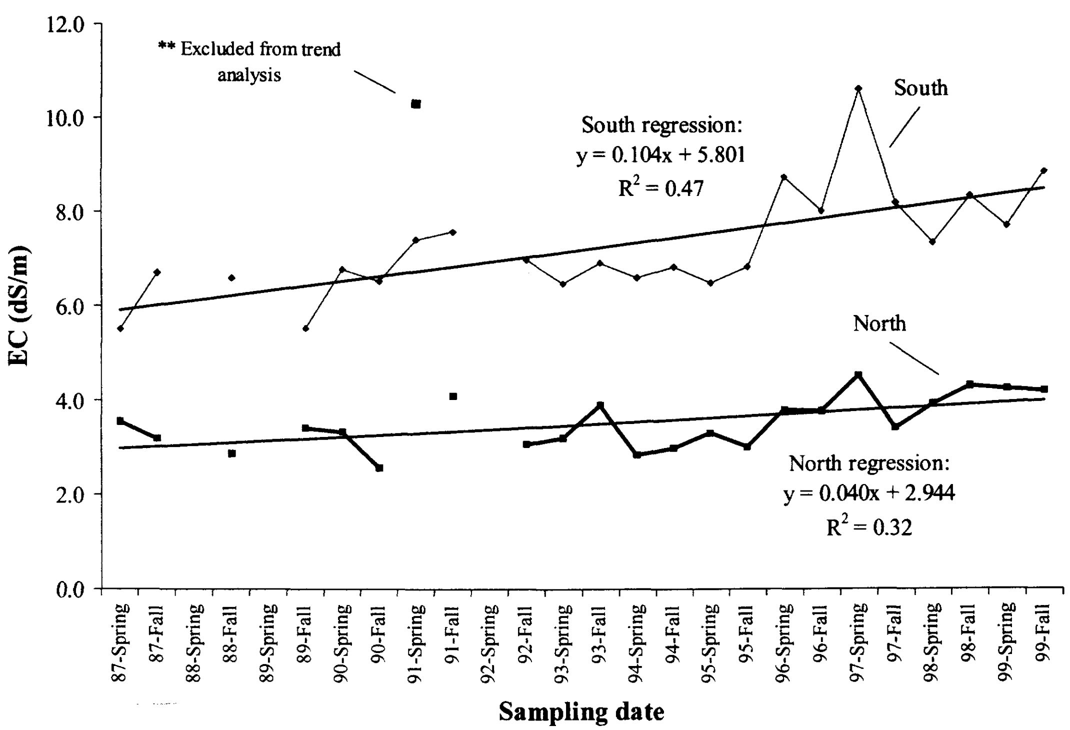


Figure 4.29: Electrical conductivity of water sampled from monitoring wells.

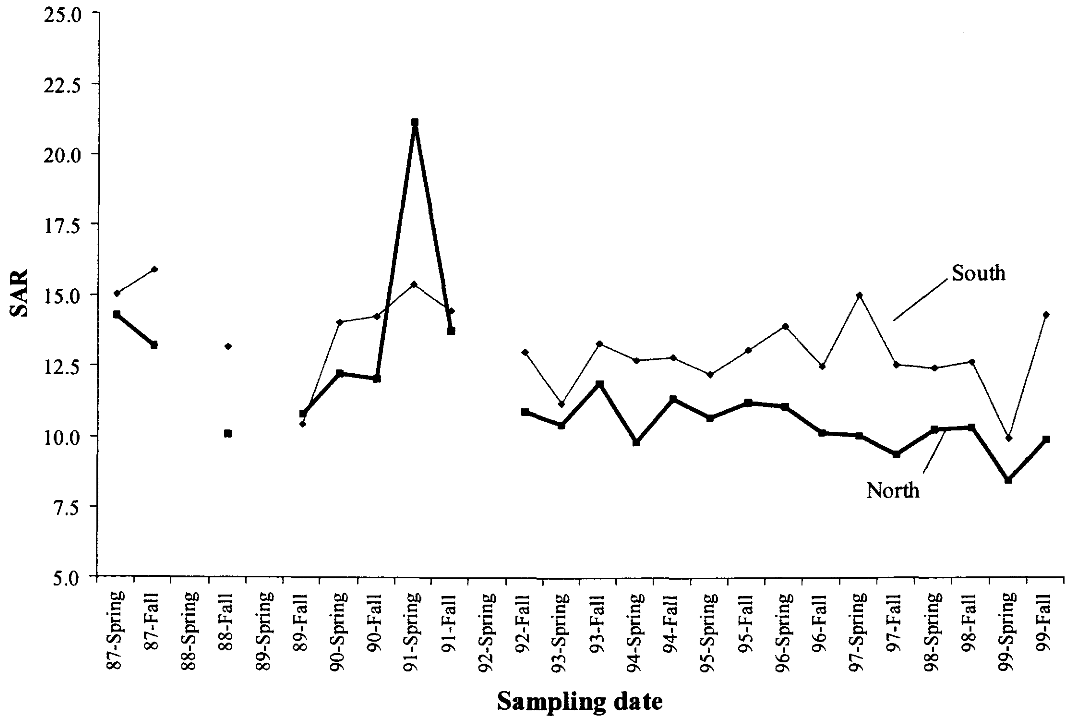


Figure 4.30: Sodium adsorption ratio (SAR) of water sampled from monitoring wells.

*ii. **Drainage effluent***

Chemical analysis, completed on drain effluent samples, is presented for each of the drainage systems in Tables 4.5 and 4.6. The values presented are average values for the entire year.

Table 4.5: Traditional drainage system (south parcel) water quality.

Year	pH	EC (dS/m)	SAR
1993	8.2 (0.23)	6.5 (0.49)	12.2 (0.61)
1994	8.2 (0.20)	6.5 (0.86)	12.5 (1.00)
1995	8.1 (0.16)	6.6 (0.59)	12.3 (0.56)
1996	8.2 (0.27)	7.0 (1.09)	11.5 (1.10)
1997	7.9 (0.33)	7.6 (0.92)	12.0 (0.96)
1998	8.4 (0.19)	7.6 (0.45)	11.8 (0.64)
1999	8.3 (0.24)	7.9 (0.27)	12.2 (0.33)
Average	8.2 (0.23)	7.1 (0.67)	12.1 (0.74)

(Values in brackets are standard deviations of the means)

Table 4.6: Experimental drainage system water quality

Year	Depth	pH	EC (dS/m)	SAR
1998	Shallow	8.1 (0.45)	4.8 (0.58)	9.5 (1.06)
1999	Shallow	8.3 (0.41)	4.5 (0.10)	9.3 (0.84)
1998	Deep	8.0 (0.47)	4.7 (0.14)	9.4 (0.41)

(Values in brackets are standard deviations of the means)

With respect to Table 4.5, the pH of the traditional system effluent varied somewhat, year to year, but generally remained slightly over 8. The EC, however, increased over the years. The SAR does not appear to be correlated with EC and ranged from 11.54 to 12.53.

Variation of EC with flow rate is apparent in Figure 4.31, where the EC ranged from around 6 dS/m during low flow rates to almost 10 dS/m during peak flows. Figure 4.32, showing the variation of $SO4^{2-}$, Na^{+}, Mg^{2+}, and Ca^{2+}, indicates a similar response to flow rate with the exception of Ca^{2+}, which tended to stay near constant levels. From comparison of Table 4.5, Figure 4.31, and Figure 4.32 it is noted that the EC tended to increase somewhat over the years but the dominant ions did not. These unexpected results will be discussed in later sections.

The experimental system (Table 4.6) produced quite different water quality than the traditional system (Table 4.5). The pH was approximately the same, the EC was 2-3 dS/m lower, and the SAR ranged around 2-3 units lower. There did not appear to be any obvious differences in water quality between the shallow and deep depth of the experimental system.

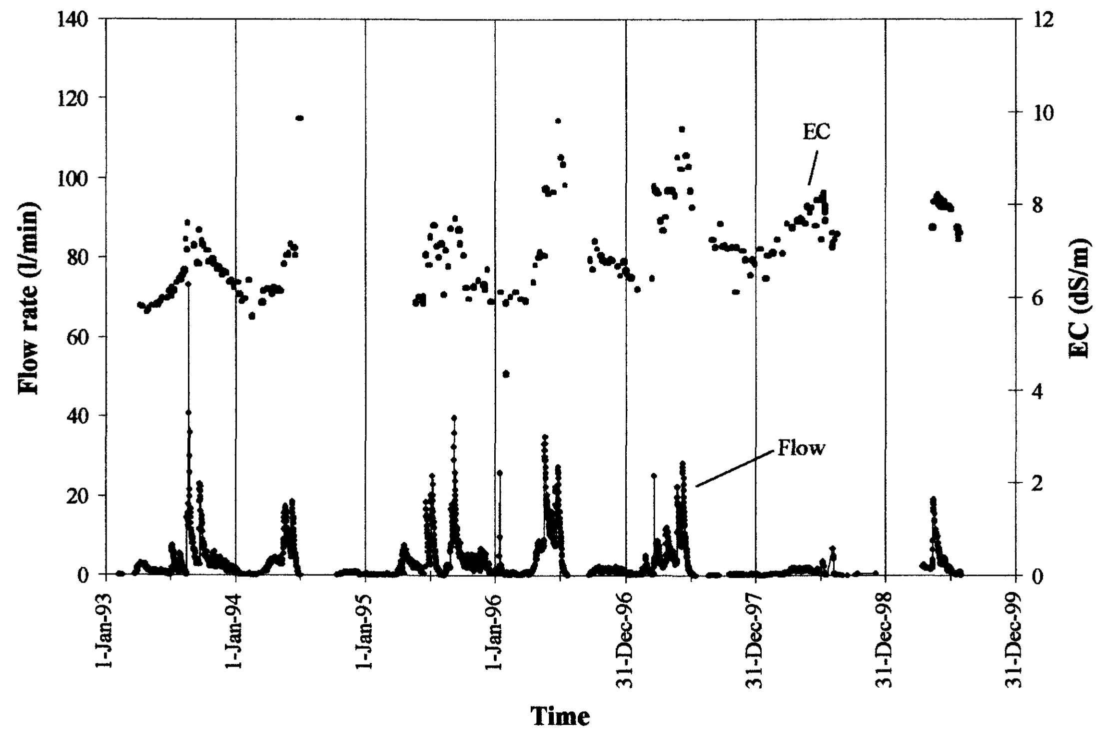


Figure 4.31: Comparison of traditional drainage system discharge rate and discharge EC (south parcel).

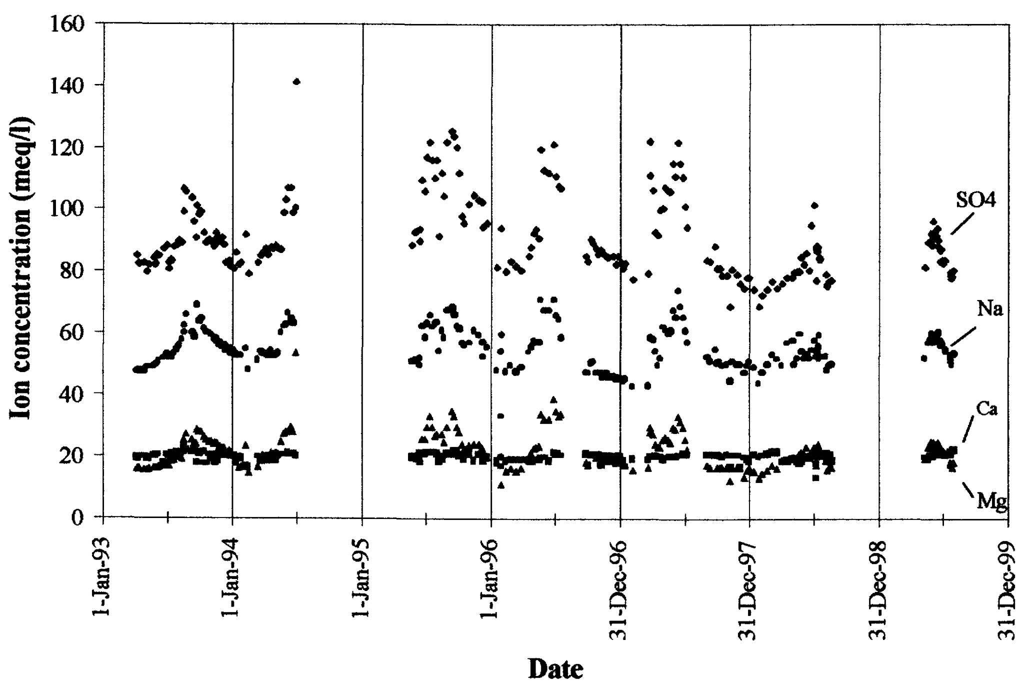


Figure 4.32: Temporal variation of major ions in traditional drainage system discharge samples.

5. DISCUSSION

5.1 Traditional Drainage System (South Parcel)

5.1.1 Water table control

The data from early years (pre-1998) provided an opportunity to compare the pre-drainage and post-drainage hydrology of the south parcel with that of the untreated north parcel. If it could first be established that the two parcels reacted in a very similar manner before either drainage system was installed, then any observed changes in the hydrology of one parcel after the treatment would then indicate the effects of the drainage system.

The water table elevations shown in Figure 4.8 for the years 1987 to 1990 indicate that there is a relation between the two parcels in terms of water table position in the way that they both fluctuated at a similar frequency and magnitude. To determine the level of correlation, north and south parcel water table elevations (group of averaged wells) were plotted against each other for two periods as shown in Figure 5.1. The periods plotted represent pre-drainage (Aug. 19th, 1987 to Aug. 31st, 1990) and post-drainage of the south parcel (Sept. 1st, 1990 to Jun. 30th, 1998, and Sept. 16th, 1998 to May 10th 1999). The post drainage periods were chosen as to include only those times when the experimental system in the north parcel was closed. As seen in Figure 5.1, the before drainage and after drainage water table elevations are highly correlated (r^2=0.87

and r^2=0.82 respectively) indicating that the two parcels are influenced by the same climatic factors, and respond in a very similar manner, particularly in the untreated state.

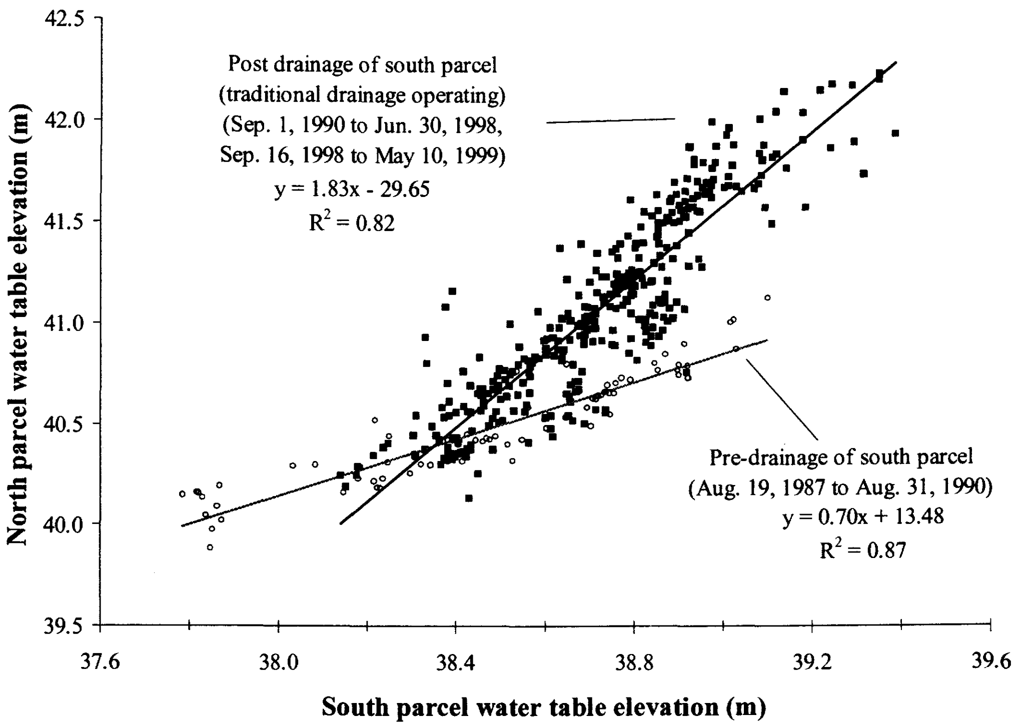


Figure 5.1: Correlation of north and south parcel water table elevations, before and after installation of the traditional drainage system in the south parcel.
Note: data collected prior to 1997 were collected by Agriculture and Agri-Food Canada, data collected from 1997 – 1999 were collected jointly by Agriculture and Agri-Food Canada and the author).

Pre-drainage (1987 through 1990) mean annual precipitation was 309 mm and the post drainage (1991 through 1998) average was 412 mm. This increase in precipitation might suggest that the water table elevations of both parcels would likely be higher in the post-drainage period than in the pre-drainage period. However, inspection of Figure 5.1 reveals that the water tables in the north parcel rise a relatively greater distance than those in the south parcel do during the wetter post-drainage period.

Statistical analyses of the two trend lines, based on the selected well data, (Figure 5.1) indicate that there is a significant difference (α=0.05) between the slope of the pre-drainage trend line and the slope of the post-drainage trend line. This change in slope would indicate that the traditional drainage system was preventing water table elevations in the south parcel from rising as much as they would have in the untreated state. For example, the highest north parcel elevation observed during the post-drainage period was well over 100 cm greater than the highest observation during the pre-drainage period. In the same manner, the peak south parcel elevation was only around 30 cm higher in the post-drainage period than in the pre-drainage period. The slope indicated by the regression line for the pre-drainage period would suggest that the south parcel water table would rise by 70 % of the north parcel rise in elevation had the two parcels remained in the untreated state. However, in reality the south parcel water table only increased by 30 % of the observed rise in the north parcel, indicating that the traditional drainage system in the south parcel has had a marked impact on the hydrology of the south parcel.

Another interesting observation is the effect of the traditional drainage system on the annual ranges of water tables. Table 5.1 presents the average mean annual water table depths as well as the average maximum and minimum depths during the pre-drainage (1987-1990) and post-drainage (south parcel, 1991-1997) periods for both parcels. These data are presented for individual years in Figure 5.2. Mean water table depths are calculated as the average of all days in which the blocks of wells in both parcels were measured on the same day.

In the pre-drainage period of the south parcel, the magnitude of the ranges of water table depths observed were fairly similar for the north and south parcels with the range averaging slightly larger for the south parcel (Figure 5.2). However, after drainage of the south parcel, the annual ranges of water table depths were smaller and the average depths were greater for the south parcel than the north parcel. Note that the average values for the south parcel (Table 5.1) in the much wetter post-drainage period were similar to those of the pre-drainage period. Conversely, the mean values for the north parcel showed much higher water table conditions during the latter period. Based on the analysis method used in this thesis, it appears that the traditional drainage system acted to reduce the annual minimum and mean water table depth of the south parcel as compared to the undrained north parcel.

Table 5.1: Period averages of mean, maximum, and minimum water table depths (m).

	South Parcel (Traditional)			North Parcel (Experimental)		
Year	**Min.**	**Max.**	**Ave.**	**Min.**	**Max.**	**Ave.**
87-90	1.64	2.46	2.08	1.50	2.18	1.89
91-97	1.32	2.13	1.78	0.35	1.83	1.23

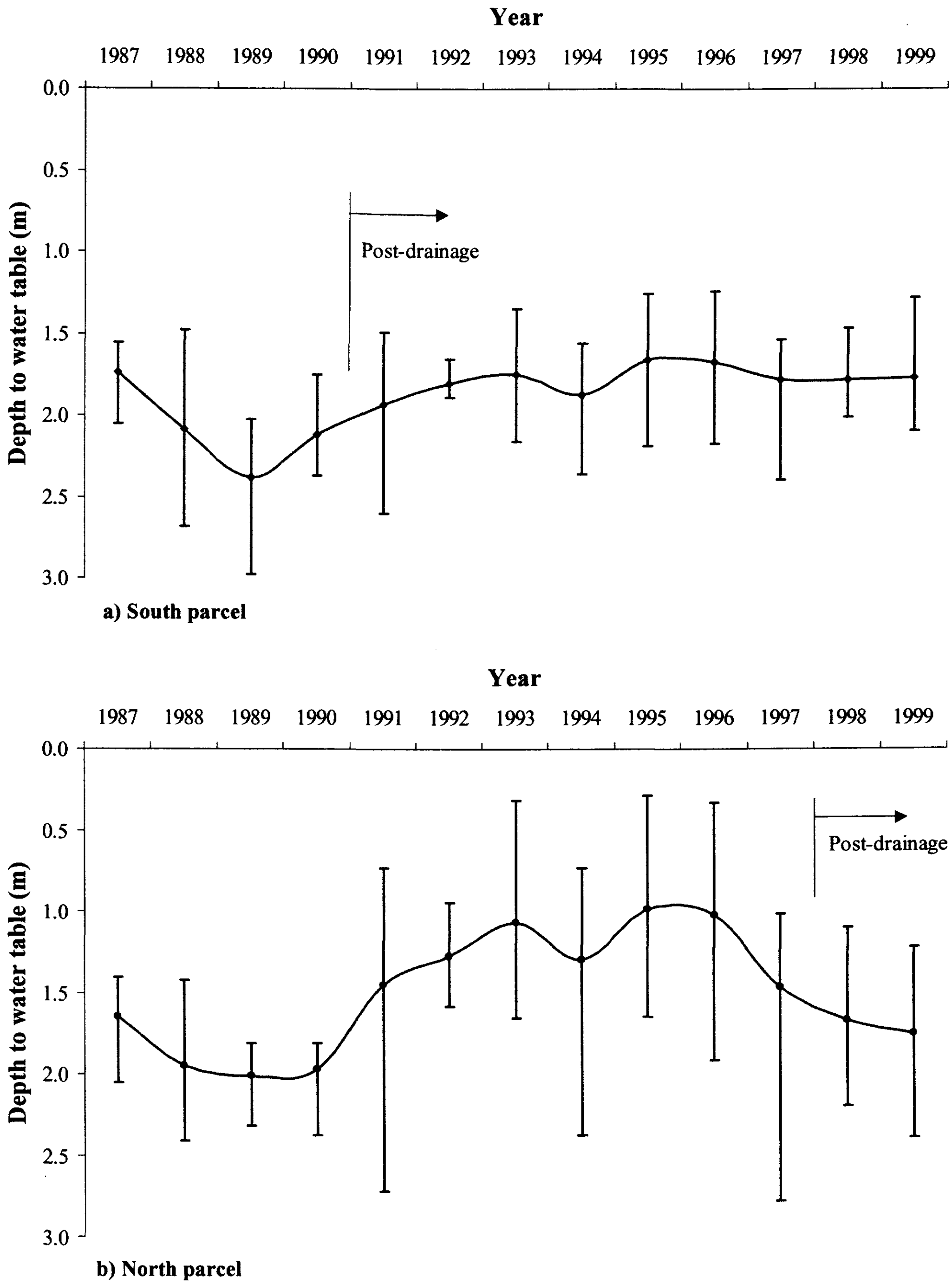


Figure 5.2: Mean water table depth for (a) south parcel and (b) north parcel.
Note: Error bars represent yearly maximum and minimum water table depths observed.

5.1.2 Soil salinity control

There are a number of factors that contribute to the salinity levels observed at a particular site. Most important, are the environmental conditions necessary to cause salinization: low precipitation and high evapotranspiration. In consideration of April-October climate at this site (warm season, Figure 4.1), the post-drainage period (of the south parcel) experienced a much smaller water deficit (average = 134 mm, 1991-1999) than the pre-drainage period (average = 239 mm, 1985-1990). One would expect to see less salinization occurring in the post-drainage period as a result of the smaller amounts of energy available for evapotranspiration and the larger amounts of precipitation available for leaching salts downward.

To investigate this theory for the site under study, relative changes in April-October water deficit and EC_e (0-30 cm) for the south and north parcels are presented in Table 5.2. Notice that the direction of the change from year to year in EC_e of the south parcel corresponds to the direction of change in water deficit for all of the years presented. Dissimilarly, the north parcel does not correspond in direction for three years. As shown in Table 5.1 the water table under the south parcel was maintained at a much greater average depth from the surface than the north parcel (1.78 m compared to 1.23 m) during the post-drainage years of 1990 through 1997. It is likely that the reduction in EC_e of the south parcel relative to the north parcel (Figure 4.26) is due, in part, to the drainage system. That is, the traditional drainage system maintained a low enough water table that the main factors influencing soil salinity in the upper 30 cm were the previously mentioned environmental conditions. For example, the large amount of summer precipitation received in 1991 (302 mm, Table 4.1) contributed to lowering soil salinity of the 0-30 cm depth interval by 3 dS/m in one year after installation of the traditional drainage system. During 1991, the shallowest observed water table depth was approximately 1.2 m from the surface. For the same period the north parcel EC_e (0-30 cm) had increased by 1.3 dS/m, indicating that the precipitation may have actually contributed to the salinity problem of the north parcel as the average water table was observed to rise to within 0.18 m from the soil surface.

Table 5.2: Direction of change of April to October water deficit and EC_e (0-30 cm) of the south and north parcels.

Year	Change in moisture deficit (Apr.-Oct.)	Change in EC_e (South Parcel)	Change in EC_e (North Parcel)
88-89	-	-	-
89-90	+	+	+
90-91	-	-	+
91-92	+	+	+
92-93	-	-	-
93-94	+	+	+
94-95	-	-	+
95-96	+	+	+
96-97	+	+	-
97-98	+	+	+
98-99	-	-	-

Note: EC_e of the 0-30 cm depth was calculated as the average of the 0-15 cm and 15-30 cm depths. The '+' and '-' signs in the table refer to an increase or decrease in moisture deficit or EC_e as compared to the previous period. Eg. for 89-90 the moisture deficit was larger than that of 88-89 and the EC_e increased for the south and north parcels relative to the EC_e levels of 88-89.

The lower soil depths are obviously not as influenced by climatic conditions, and consequently it is difficult to explain all of the curves presented in Figures 4.26a. In comparison of 1999 levels to 1990 levels (prior to installation of traditional drainage system), the 30-45 cm and 45-60 cm depths have decreased in salinity, whereas the 60-75 cm and 75-90 cm depth intervals have increased in salinity, resulting in the four curves to converge somewhat. This could possibly indicate that salts were moving downwards in the profile as a result of the continuous downward moisture flux created by the drainage system.

Based on the monitoring strategy and analysis used for this thesis, it is difficult to draw any firm conclusions as to the effectiveness of the traditional drainage system at lowering the total dissolved solids of the soil solution above the drain lines. After 9 years of drainage the salinity of the upper 60 cm of the soil profile has been decreased. However, in terms of total root-zone desalinization, the entire 0-90 cm profile was only reduced by 0.89 dS/m. Crop growth has been made possible on the parcel every year since the traditional drainage system was installed indicating that the drainage system has had a positive effect on soil salinity as it relates to plant growth.

5.1.3 Water quality

As seen in Figure 4.32, there appears to be a relationship between drainage effluent flow rate and drainage effluent EC, where the peak flow rates correspond to high EC values. Also, previously presented in Figures 4.17 through 4.20, flow rate is highly dependent on precipitation, particularly regarding peak flows. Therefore it appears that the drainage water EC is higher during large precipitation/infiltration events. The increase in EC during these events is likely due to salts being leached down from higher profiles into the drains. This observation can be used to further corroborate the suggestion that the drainage system is removing salts from the soil profile. Doering and Sandoval (1981) report that for a saline seep in North Dakota, the concentrations of the ions did not depend on flow rates. The seep presented by these authors was supplied by saline groundwater originating from a source some distance away from the discharge area. The results from this study can be used to validate the notion that the waters supplying this seep are originating locally and have a relatively short residence time in the ground and are consequently more variable in quality.

To further investigate the relationship between flow rate and EC values, the compositions of all drain samples were compared and no major differences in terms of relative composition were found among different EC values. The SO_4^{2-} + Cl^- content was found to vary between 40-57% of total ion content, and the Na^+ + K^+ content varied between 26-31 % over the entire range of EC values. This would indicate that water of similar quality (likely from the same source) was supplying the seep area during peak flow and low flow periods.

The fluctuating EC values also indicate that the chemical analysis of the water samples taken biannually from monitoring wells are quite time dependant, and would give very different results if sampled during a high precipitation period. This could explain some of the anomalies presented in Figures 4.27a (spring 97) and 4.27b (spring 90, and spring 92) where monitoring wells exhibited much higher salinity in certain years than others. It is not known exactly why these anomalous values would appear in one parcel during a year and not the other, as both parcels were sampled on the same day. High precipitation could have transported salts concentrated near the surface downward to the depth of the monitoring wells. However, the averaged discharge EC is usually much lower than these anomalous values, indicating that whatever process is causing them is not significant when considered over a time period of one year.

The EC of the traditional system discharge water (Table 4.5) and the EC of the south parcel monitoring wells (Figure 4.29) seemed to be increasing over the measurement period. This would mean that the water quality of the effluent would be getting less suitable for discharging or re-using downstream. However, this result is somewhat questionable, because the major ions of the discharge water did not increase over the study period (Figure 4.32). It is not known whether this discrepancy can be attributed to an error in the EC meter calibration or due to an increase of some other ion that was not tested. The EC meters were calibrated using to a standard solution every year so it is likely that this would only be a minor source of error. Possible ions that could be increasing but were not measured for are HCO_3^{-2} or NO_3^-.

In order to investigate any differences in water quality between the traditional system discharge and the monitoring wells, the composition of the two waters were compared in Figure 5.3 showing the relative percentage of cations and anions in a groundwater composition plot. As seen here, the relative compositions of the waters are quite similar, with the monitoring wells exhibiting slightly higher proportions of Na^+ + K^+ than found in the drain discharge. This could reflect the fact that a number of the monitoring wells used for calculating the average value extend to a depth below the drains and in some cases into the underlying shale layer. At this site it has been determined that the underlying Bearpaw shale layer contributed excess salts, including Na^+, to root zones (H. Steppuhn, Research Scientist, Swift Current).

As seen from the simultaneous response in water table heights, high rainfall events, outflow discharge rates, and similar chemical composition (Figure 5.3), the discharge waters of the traditional drainage system originate from local infiltration events. Flow to the drainage system occurs through consequent vertical soil drainage as well as through the weathered, relatively permeable shale-till contact layer.

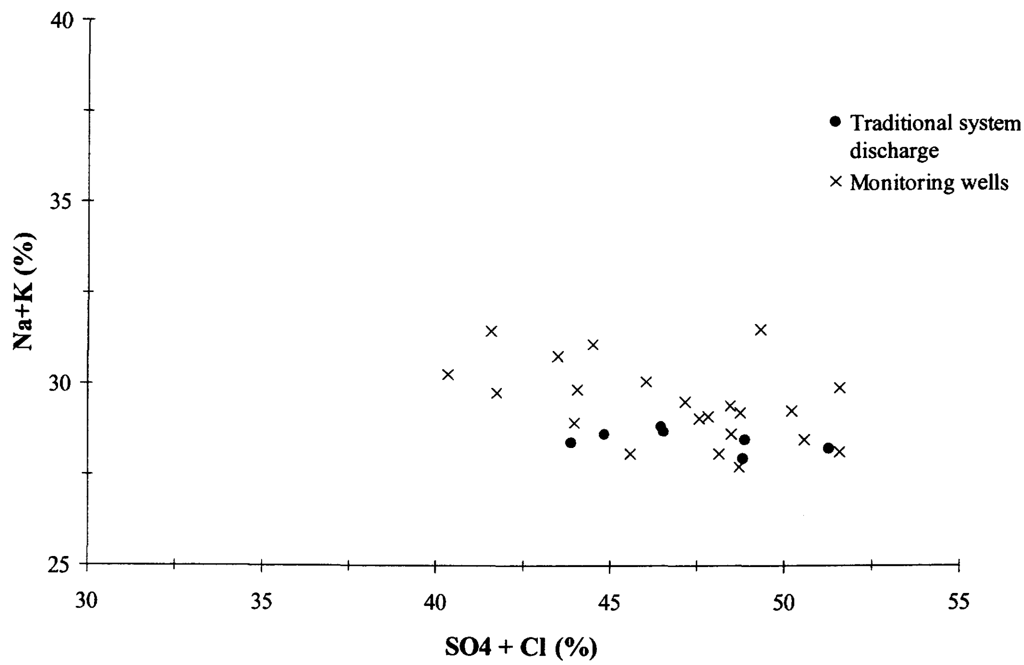


Figure 5.3: Composition diagram of south parcel waters.
Note: Each discharge point represents a yearly average and each monitoring well point represents the average of a group of wells measured at a single point in time.

5.2 Experimental Drainage System

5.2.1 Water table control

a) Water table depth

In this experiment, two very different water management schemes were used for the experimental drainage system during 1998 and 1999. In 1998 the drain was opened periodically, releasing enough water to lower the water table. In 1999, the drainage system was left open continuously from May through August. Each management strategy represents the extreme end of a typical water management plan. For instance, the short drainage events completed in 1998 are probably more frequent and shorter than a typical landowner would use and represent a "worst-case" scenario. Likewise, during 1999, the drainage system was opened continuously, opting not to take advantage of any water management plan at all. The original design criteria for the study was to develop a drainage system that could be used with a water management plan that would release enough water to minimize the salinization hazard, yet only do so at strategic times when water was needed for down-slope uses. Therefore, the two years of data are representative of over and under utilization of the designed plan.

In determining whether or not the experimental system is capable of lowering the water table rapidly enough to prevent salinization, the water management plan used must be taken into consideration. With a non-valved system, it is relatively simple to determine whether the drain performance is adequate to minimize salinization; if the water table rises a significant distance above the drains, the drainage system performance is unacceptable. However, with a valve-controlled system such as the experimental one tested in this study, the water table may be allowed to rise well above the drain lines as part of the water management plan. In such cases, as it was in both years of this study, other performance indicators must be used. The most important of these is the ability to lower the water table quickly to a depth corresponding to a low salinization risk. Most drainage systems are installed at the deepest depth that is economically feasible. With most modern drainage equipment this is around 1.8 m, the same depth at which the shallow option of this system is installed. Therefore, a safe water table depth would be around 1.5 m from the surface. This depth would likely prevent the capillary fringe from the water table from extending very far into the root zone and would still allow 30 cm of water above the drains for 'on-demand' re-use of the water down-slope.

In 1998, the average water table in the north parcel was around 1 m below the soil surface (Figure 4.23) before the first drainage operation. The net change in water table elevation, calculated as the difference between the water table depth immediately before a particular drainage operation and immediately prior to the next drainage operation, of the first two drainage operations were around 40 cm each, lowering the average water table to the shallow drain depth (1.8 m). The first two drainage operations were 51 and 74 hours long respectively; thus, it would appear that the average water table could be lowered quite quickly. However, well 5046 does not respond to the drainage operations as quickly as the averaged group of wells. The fact that the water level in well 5046 (Figure 4.23) is shallower than the group of averaged wells indicates that the slope of the water table is different than that of the ground. This difference also indicates that the water level of the east side of the parcel takes longer to lower to a safe depth. Note that the water level in well 5046 does not reach 1.5 m below the surface until July 18th.

In 1999, the water levels in the group of averaged wells and in well 5046 displayed consistent drawdowns while the drainage system was operating (Figure 4.25). After the drainage system was started (May 20th), the depth to water table was lowered to 1.5 m in the averaged wells by May 31st and in well 5046 by June 19th, despite the fact that heavy precipitation (240 mm, May 1 – Jul. 31) occurred during this time, and the flow rate of the drainage system was quite low. The response of the water table to varying flow rates suggests that a minimum flow rate is needed to lower the water table. For example, when the flow rate was lowered to below 5 ℓ/min (June 11th to June 14th) the water table was observed to begin to rise again. This minimum drainage rate will be a function of the amount of precipitation received during the period.

b) Soil moisture

Based on water table depth and outflow information only, it is difficult to quantify exactly how large of a contribution to the water table decline can be attributed to the drainage system and how much water seeps to lower elevations or how much evaporates. This is particularly true, when a significant capillary fringe exists, as only a small change in the amount of water stored is then required to raise or lower the water table relatively large distances (Gillham 1983).

Soil moisture measurements obtained during 1998 provide some insight as to the actual effectiveness of the drainage systems at lowering water tables. Figures 4.15 and 4.16, representing south and north moisture contents respectively, show important differences between the traditional and experimental drainage systems and the effect of their operation on moisture contents. When assessing these differences it is useful to relate this information to the amount of precipitation received during the period and the water table depth on the day of measurement. Table 5.3 presents this information as well as the average moisture content and saturation ratio of the root zone (0-120 cm) for each parcel.

Table 5.3: Soil moisture analysis of root zone (0–1.2 m) for 1998.

		South Parcel			North Parcel		
	Period Precip (mm)	**Sat. Ratio**	**Moisture Content (mmH2O)**	**Depth to Water (m)**	**Sat. Ratio**	**Moisture Content (mmH2O)**	**Depth to Water Table (m)**
May 8th	-	0.67	377	1.64	0.76	403	1.33
Jun. 5th	29	0.68	378	1.65	0.78	413	1.30
Jul. 8th	92	0.70	389	1.72	0.79	419	1.38
Jul. 17th	0	0.70	394	1.75	0.76	402	1.88
Aug. 12th	40	0.66	370	1.74	0.70	372	2.16
Aug. 26th	6	0.65	366	1.86	0.67	358	2.28

Note: the period precipitation was obtained from an on-site standard rain gauge and represents the amount of precipitation received since the previous date.

With respect to Figure 4.15 and Table 5.3, the south parcel information represents the moisture distribution under a nearly constant water table. Note how the water table depth only changed by 0.2 m between the first and last moisture measurement (Table 5.3). From inspection of Figure 4.15, the only major change in soil moisture occurred in the top 65 cm, as seen in the July 8th measurement, and is likely due to the site receiving 121 mm of precipitation since the first measurement.

With respect to the experimental system (Figure 4.16), at early dates (up to and including July 8th) the saturation ratio of the root zone was 9-10 % higher (Table 5.3) than that found in the south parcel (traditional system). The high water table observed in the north parcel during these dates likely contributes to this difference.

5.2.2 Soil salinity control

With most dryland salinity, in the absence of large amounts of leaching water, desalinization rates are generally expected to be quite slow (Paterson and Jensen 1984). This statement is supported by a study in which Buckland and Hendry (1992) did not find any reductions in soil EC of the soil profile (0-1.2 m) after three years of a drainage study located in Southern Alberta. The length of this project is likely insufficient to indicate a significant reduction of the soil profile EC. However, there is still some merit in discussing soil salt dynamics with respect to this system. From inspection of Figure 4.26b, there are no obvious declines in the salinity levels of the saturated extracts of the north parcel during 1998 and 1999 except for that observed in the top 15 cm. In fact, salinity levels (0-90 cm average) have increased by 1.7 dS/m since the experimental system was installed in 1997. In comparison to the south parcel, by 1992, after two years of operation, the average EC_e of the soil profile (0-90 cm) had decreased by 0.6 dS/m.

There may be a couple of reasons for this. First of all, in 1998 the drainage system was not opened until July 7th (later than what normally would be desired), allowing the water table to rise within 0.3 m of the soil surface (well 5046) so that additional salts may have been transported to the upper soil profile. Also, the April-October water deficit (Figure 4.1) calculated for 1999 (168 mm) was much larger than that experienced in 1991 (56 mm). As previously discussed in relation to the traditional drainage system it is believed that the April – October moisture deficit plays a key role in influencing the EC_e of the upper 30 cm of the soil profile.

However, from a practical perspective, the installation of the experimental drainage system did result in increased crop growth in 1999. This is most likely due, in part, to the greater precipitation volumes that occurred from May to July (240 mm) that provided leaching waters to dilute the strength of the salts that were present within the seedbed and root zone. Also, the May-July water deficit calculated in Figure 4.1 is negative for 1999, similar to that experienced in 1991. In both of these years, a crop was established for the first time. The installation of the experimental drainage system likely played a key role in establishing the crop in the north parcel by draining the excess water and establishing a downward potentiometric gradient. By late July and August, the months normally associated with high evaporation rates, the water table under the parcel was below 1.5 m from the surface (Figure 4.25). This eliminated a significant flow path from the water table to the soil surface from occurring, and thereby prevented resalinization of the soil.

The length of this study is insufficient to properly evaluate the effectiveness of the experimental drainage system at reducing soil salinity. However, some benefit to the soil was observed, as a crop was grown in 1999 for the first time on the north parcel.

More years of data are needed to determine whether or not the experimental system will be as effective as the traditional drainage system or whether or not the non-continuous operation of the drainage system will have any adverse effects on soil salinity.

5.2.3 Drainage system as a water source

The ability of the experimental system to act as a water source, although not a trait used to evaluate performance in this study, is important to examine because it provides a great deal of insight into the hydraulics of the drainage system. The periodic operation of the experimental drainage system during 1998 reveals some unique features of the system. With respect to Figure 4.22, a maximum flow rate of approximately 22 l/min was observed. As soon as the depth of water in the drainage well reached 1.8 m the flow rate rapidly declined. The abrupt transition to a lower flow rate likely marks time of de-watering for the gravel-filled porous regions around the drainage lines and the well. When this happens, the drain lines conducting water to the measurement station stop flowing full (the pipes are no longer submerged) and the flow rate consequently becomes dictated by the hydraulic flux of the surrounding soil matrix rather than by the capacity of the piping system.

After the drain is closed, the water level in the drainage well begins to quickly recover (Figure 4.22). This is likely due to water, as it is redistributed, moving from the surrounding soil matrix to the highly permeable gravel regions surrounding the well and the lines. The water level in the drainage well would not be expected to recover so rapidly had the surrounding soil formation been completely drained. However the rapid recovery of the water level would indicate that the porous regions surrounding the well and drain lines seem to act as a reservoir that can be emptied and filled relatively quickly. That is, the water within the gravel filled trenches leaves the system first, creating a large seepage face between the trench and the soil formation. After the drain is shut off, the water being conducted to this seepage face from the soil acts to re-fill the trench space. It is expected that the recovery volume will be considerably less than productive yield of the aquifer that was indicated when the water table was lowered. This is due to the effect of entrapped air below the water table (Bouwer 1978). This effect could also be partly responsible for the rapid increase in water tables observed following closure of the drainage valve.

It is not exactly clear why the flow rate of the drainage system was limited to a maximum of 22 l/min (Figure 4.22). The fact that the flow rate did not change as the water in the drainage well was lowered indicates that the measurement system is in error or some mechanism of pressure compensation was occurring. The measurement system is capable of, and has been tested at, measuring higher flow rates than this so this point does not likely mark the highest measurable flow rate. One possibility is that one of the valves used to regulate flow could have been providing pressure compensation. This valve was a gate-type valve constructed of a thin polyethylene that was noticed to deform under pressure to such an extent that the gate could not be closed again until the pressure acting on the valve had subsided. In any case, the second drainage operation shows a much more reasonable peak-flow curve where the flow rate is noticed to have decreased as the water level in the drainage well was lowered. The poor performance of this valve did not affect the measured flow rate in any way other than by masking the typical pressure-flow relationship that should exist. The data collected by the datalogger is still deemed to be accurate.

In both 1998 and 1999, the deeper option of the experimental drainage system did not supply an appreciably increased amount of water over the shallow depth (Table 4.4). This can be attributed to the way that the system was designed and operated. For instance, in both years, by the time that the deeper option was opened, the average water table within the parcel had already been lowered to below 2 m due to the long operation period of the shallow option.

Installing the system perpendicular to the ground contour, with the drainage well at the lowest elevation also conceals the effect of the deeper drainage system because the amount of readily available water cannot easily be separated between the two depths. As seen in Figure 3.5, when operating the shallow depth option, the gravel filled region separating the two depths would act to conduct water from below the shallow option of the upper lateral down to the drainage well. This would act to overestimate the amount of readily available water produced by the shallow system and underestimate that of the deeper depth. It is important to consider the fact that, had the shallow system been installed separately, gravel would not have been placed in the trench and the amount of readily available water would likely be significantly reduced. Obviously, this system would be better tested in a flatter area. Nonetheless, if the shallow drainage system did not exist, the deeper system would be expected to produce a considerably higher amount of readily available water than the shallow option because of the increased volume of the gravel filled region and the larger seepage face created by the drainage trench.

During 1999 (Figure 4.24), by allowing the flow through the drain to be regulated by the irrigation system, the water within the drainage well was not lowered to the drain depth of the shallow system until the 9th of June. Up to this point, (20 days after opening) approximately 167 m^3 had passed through the system. Although the flow through the system was not constant, this does indicate that a sufficient amount of water will be available for most downstream uses from either depth option. Notice that even though the water level in the drainage well was at the shallow drain depth (1.83 m), a significant continuous flow rate (approximately 10 ℓ/min) was still maintained.

From inspection of Figure 4.25, we can see that on June 12th, the water level in the group of averaged wells was near the shallow drain depth (1.8 m), yet the water level in well 5046 was still at a depth of approximately 1.45 m. The fact that the water table in 5046 was higher than the average water table would indicate that most of the water supplying the drainage system at this time was entering into the lower drain lateral or directly into the drainage well. This would suggest that the upper lateral (Figure 3.5) was no longer contributing to the flow, even though the drainage system had only been opened for approximately 20 days. This again is reflective of one of the inefficiencies associated with installing a drainage system on a slope.

It is difficult to estimate the amount of water that will be available for a given year. The amount available is dependent on the water table depth before drainage is started, the moisture content of the soil above the drains, the amount of precipitation received during the summer, and the amount of water used by evapotranspiration. During 1999, the experimental drainage system produced over 600 m^3 of water, even though the system was not opened until May 20th. Had the system been opened earlier, perhaps even more water could have been supplied. The year of 1999 received above average precipitation, and the moisture content above the drains was high, providing good opportunity for large recharge rates to occur. Consequently, 1999 may represent a best case scenario for water supply amounts. It can be projected that if the north parcel continues to grow a crop every year the amount of available water will be reduced due to a decrease in the amount of recharge to the local ground water table as the vegetative water requirement will be much larger.

5.2.4 Water quality

Figure 5.4 compares the composition of the effluents of the two drain depths, and the waters extracted from the monitoring wells. The compositions of the drain discharges are fairly similar to the water in the formation (monitoring wells). The water from the monitoring wells indicates a slightly higher proportion of Na + K than the discharge waters, reflecting that some of the wells used in calculating the average extend into the underlying shale. There does not appear to be a discernable difference in composition between the shallow and deeper systems.

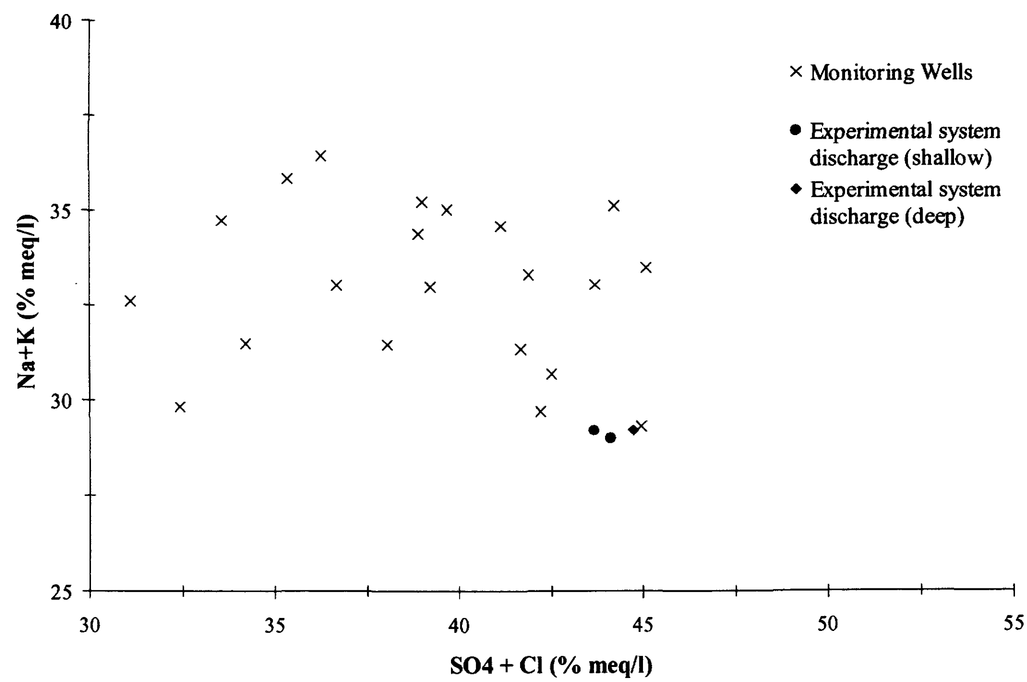


Figure 5.4: Composition diagram of north parcel waters.
Note: Each discharge point represents a yearly average and each monitoring well point represents the average of a group of wells measured at a single point in time.

5.3 Drainage System Suitability

One of the purposes of this work was to identify and recommend certain aspects of the drainage systems and water management plans tested in this study that are suitable to the needs of producers located within the semiarid prairies. In order to do this, it is necessary to discuss any differences between the systems relative to operating plans, design criteria, and physical characteristics. The three items most important to a successful drainage project are water table control, salinity amelioration, and water quality / re-use considerations.

5.3.1 Water table control

a) Evaluation

Since installation of the traditional drainage system, the hydrology of the south parcel has been altered with respect to its own pre-drainage state (Table 5.1) and that of the north parcel (Figure 5.1). Despite higher average annual precipitation received in the study years following drainage, the average water table under the south parcel had been maintained at approximately drain depth (Table 5.1) indicating that the drain was operating as designed.

The experimental system, although operated much differently than the traditional system, also lowered the water table when the valve was opened (Figures 4.23 and 4.25). The design objective of this system was to lower water tables by releasing enough water to prevent salinization and to supply an irrigation system. In most instances, an average water table depth of greater than 1.5 m is desirable. In this study the water table was allowed to rise to within 1 m of the surface in both years because of the obligation to release the water according to the requirements of the downstream use. However, the time taken to lower the water table to a safe depth of 1.5 m was relatively short: around 10 days in 1998 and 11 days in 1999. The time taken to lower the water level within well 5046 to a depth of 1.5 m was around 12 days in 1998 and around 30 days in 1999.

In 1998 the experimental system was operated less than what would be expected for a normal year. However, the water table was lowered to a safe depth (Figure 4.23) and a large reduction in soil moisture (Figure 4.16) resulted. In 1999, again the water table was allowed to rise to near the surface but was then drained continuously resulting in a large volume of water released (> 600 m^3) through the system. Even at the low flow rates used in 1999, the water table continued to drop (Figure 4.25) despite the fact that the site received considerable May – July precipitation (240 mm).

In this study, the traditional drainage system performed superior to the experimental system in that it consistently maintained a low water table. Since the installation of the traditional drainage system, the water table depth in the south parcel has not presented a salinization hazard. However, in the north parcel the water table was allowed to rise close enough to the soil surface that a significant salinity hazard was created in both years since the experimental drainage system was installed. This is obviously related to the operation/management of the system rather than the system itself. However, if a management plan is to be used with a drainage system, consideration must be given to releasing water through the drains early in the spring to relieve the high water tables created by snow melt or early spring rains. If the drainage system is to be used exclusively with an irrigation system, the fact that the crop will not require water until mid to late May would suggest that the salinization hazard created early in the year becomes a complication of the experimental system concept.

In any event, the deficiencies of the experimental drainage system with respect to water table control are primarily related to the management plan and not to the system design or capacity. Once the valves of the experimental system were opened, the water table under the site was controlled satisfactorily in both years tested. The smaller expanse of the experimental system does not appear to make it less capable of lowering water tables than the larger traditional system. The low flow rates (often less than 10 ℓ/min) produced by the traditional drainage system indicate that the capacity of a drainage system does not need to be that great provided that the site has a horizontal hydraulic conductivity capable of laterally conducting sufficient water towards the drains. The hydraulic conductivity of the till-shale contact layer and gravel lenses that occur at this site may be high enough that the differences between the two systems would be masked, relative to what would be observed in a homogeneous soil medium of lower hydraulic conductivity.

Summer precipitation events in the Prairie Provinces are relatively short and infrequent compared to the more humid areas where typical drainage criteria are developed. Even in the event of a large precipitation event, a small drainage system operating in the prairies will likely be able to effectively control the water table over a slightly longer period than what would normally be acceptable. A longer period to maintain control is acceptable, because the chance of receiving a number of high precipitation events in a short time is relatively small.

b) Recommendations

In terms of controlling the water table, there is some indication in this study that the experimental drainage system would be equally as effective at controlling the water table, had the system been left open year-round. Therefore, the cost difference between the two systems alone would suggest that a design similar to the experimental system should be recommended to landowners of the prairies. However, further characterization of this site with respect to hydrogeological properties may be necessary to determine if the high lateral hydraulic conductivity of this site is masking the size inequalities of these two systems.

The experimental system uses the concept of precisely placing a small amount of tubing in a specific location based on information obtained from a detailed subsurface investigation. The fact that the much smaller experimental system is similarly capable of effectively lowering water tables as the traditional system advocates this practice. Therefore, the positive results obtained from this study support the recommendation that a preliminary subsurface investigation should be completed prior to installation of drainage systems that are similar to the experimental system tested in this study.

In this study, the use of a water management plan in conjunction with the experimental drainage system confirmed that the water table depth can be effectively regulated, and that drainage is not required on a continuous basis. However, the current water management plan will have to be modified in order to lower the risk of salinization early in the year before irrigation events are normally scheduled. One recommendation that would minimize the pre-irrigation salinity hazard is to lower the water tables during the fall to the deepest depth possible. This idea advocates the use of the deep option of the experimental system. If the water tables were lowered in the fall, there would be more soil storage volume to accommodate snowmelt infiltration and any spring precipitation.

Another suggestion that would minimize the salinity hazard would be to use the system to irrigate a perennial crop such as alfalfa. This would allow for the system being opened earlier than usual, as most perennial crops require water much earlier than annual crops or trees (Saskatchewan Agricultural Services Coordinating Committee 1987).

5.3.2 Salinity control

a) Evaluation

Based on the monitoring scheme used in this thesis, the installation of the traditional drainage system in the south parcel did not result in a large overall reduction of soil salinity as the mean EC_e of the 0-90 cm profile was only seen to decrease by 0.9 dS/m as of October 1999. However, the EC_e of the 0-45 cm depth interval was reduced by 2.8 dS/m during the same period indicating that some leaching may in fact be taking place. In all years following installation of the traditional drainage system a crop was successfully grown on the south parcel, whereas none had ever grown before.

Since installation of the experimental drainage system the EC_e of the north parcel (0-90 cm) had increased by 1.7 dS/m. The 0-15 cm interval was the only depth to decrease in salinity during this period, as it was reduced by 4.8 dS/m (Figure 4.26b). During 1999, two years after installation of the experimental drainage system, an acceptable crop was produced for the first time.

The relatively small decreases in soil salinity, given that the water tables were effectively lowered and crop yields were greatly improved, present a rather unexpected result. This might indicate that the monitoring plan used does not adequately represent what is happening in the field at the plant level, or that drainage provides much more benefit to the crop than a reduction in soil salinity. Maas (1990) suggests that a plant's ability to tolerate salinity is dependent on a wide range of conditions in addition to its genetic composition. These conditions may include soil properties, water properties and climate.

Maas (1990) states that climate is probably the factor that influences plant response to salinity the most. Most crops can tolerate higher salinity levels, if the climate is cool and wet rather than hot and dry. As previously discussed in section 5.1.2, there is an indication that soil salinity is closely related to the entire warm season (April-October) water deficit. However, there may also be some indication that crop establishment is better related to the growing season (May-July) water deficit. In 1991 (post-installation of traditional system), the south parcel produced a crop for the first time. Similarly in 1999 (post-installation of experimental system, the north parcel produced a crop for the first time. Both 1990 and 1991 showed a May to July moisture surplus (Figure 4.1) reflecting the fact that there was high precipitation and low evaporative demand during this period. These conditions were ideal for establishing a crop, yet did not necessarily result in a large decrease in soil salinity throughout the soil profile in either year with the exception of the surface layers (Figure 4.26b). The effect of abundant summer precipitation is to dilute the dissolved salt content of the upper 30 cm, allowing seeds to germinate and a crop to be established. The reader should be reminded that the soil samples were taken in September or October and are not necessarily representative of what spring conditions would be.

Hoffman (1990) reports that high levels of salinity in the lower portion of the root zone have a minor effect on crop yields provided that the upper portion of the root zone has low levels of salinity. Plants have the ability to increase water uptake from areas of low salinity. This could contribute to the explanation of why crop growth was made possible in the north parcel during 1999 as the salinity level of the top 15 cm of the root zone was reduced, yet the levels of lower depths were not.

One very important factor to consider is the effect of high water tables on crop growth. Although the groundwater depth does not have a direct effect on crop growth, it is indirectly responsible for the prevailing moisture conditions, which have a profound effect on root aeration, temperature, and water supply (Wesseling 1974). Excessive soil water can decrease the amount of oxygen transfer between the atmosphere and the soil and consequently limit plant respiration and greatly effect growth. Wesseling (1974) indicates that the yield of barley (*Hordeum vulgare* L.) should not be adversely affected at a permanent water table depth of 150 cm, and would be reduced to 58 % of maximum if the water table depth were maintained at 40-50 cm. Also, regarding the effect of fluctuating water tables, it was discovered that excess water must be removed within 3 days from the root zone of alfalfa (*Medicago sativa* L.) to ensure optimum yields. Another potential concern regarding a high water table is that plants may be able to extract water directly from the water table or capillary fringe and possibly respond differently than what would be expected from the level of salinity in the soil (Maas 1990). With respect to the north parcel, from the moisture content information (Table 5.3), we can see that when the water table was near the surface, the soil profile was moist to such a degree that root aeration could possibly have been restricted.

b) Recommendations

The length of this study is not sufficient to derive recommendations for drainage design features that hasten the salinity reclamation process. Both of the systems tested have theoretical advantages that perhaps would become more apparent after long periods of time. For the traditional system, the fact that it uses twice as much perforated tubing should result in a shorter the flow path for salts leaving the soil through the drain. The experimental shallow system was designed on the premise that if the water table is controlled, no salinity hazard should exist and the extra time needed for complete reclamation does not warrant the extra installation efforts of an extensive system. The deeper system has the advantage that the water table can be lowered even further and consequently salts can be moved further away from the soil surface, greatly reducing the possibility of resalinization.

In any event, crop growth was made possible with both systems even though the salinity monitoring techniques used in this study did not reveal large decreases in soil salinity. This indicates that perhaps soil salinity is not the best variable to investigate when evaluating the effectiveness of a dryland subsurface drainage system.

5.3.3 Water quality

a) Evaluation

Based on the technique used in this thesis, the mean (n=7 years) of the annual average EC of the drainage effluent produced by the traditional drainage system was found to be 7.1 dS/m. Average annual pH for the same period was 8.2. Throughout each year the EC of the traditional drainage water seemed to vary with flow rate. The water quality of the effluent produced by the experimental drainage system is notably different than that of the traditional system. The study mean (n=2) of the annual average EC of the shallow depth of the experimental system effluent was 4.7 dS/m and the pH was 8.2. The EC (1998) of the deeper system was 4.7 dS/m and the pH (1998) was 8.0.

It is not well established as to what may be causing the observed differences in EC between the south and north parcels. From comparison of Figures 5.3 and 5.4, there is very little difference in the anion proportions between the two systems. Initial site characterization revealed that there were some differences in physical and chemical properties of the two sites. For instance, the EC_e of the 140-180 cm depth (Figure 4.6) was higher for the south parcel than the north parcel. Similarly the pH (Figure 4.5) is lower, and the clay content (Figure 4.3b) is higher at these depths in the south parcel than in the north parcel. This could reflect that the traditional drainage system is installed into a different soil layer that is more saline than that in which the experimental system is installed. Perhaps the underlying shale layer is closer to, and possibly even intersected by, some of the drain lines in the south parcel, resulting in higher ionic strengths of the traditional system discharge water. The fact that the south parcel has a lower bulk density and has a higher hydraulic conductivity than the north parcel would suggest that the relatively impermeable shale layer is not found in the south parcel. However, the till-shale contact layer could possibly exhibit a similar chemical composition to the underlying shale yet remain much more permeable. The experimental system was installed into a location where it was known that the depth to the saline shale layer was greater than 2 m.

b) Recommendations

One of the desired outcomes of this research was to recommend a drainage solution that could be transferred to other areas of the prairies. Putting the drainage water to use, such as irrigating shelterbelts as in this study, rather than simply wasting the water, supports the recommendation that the effluent should be analyzed for dissolved constituents prior to use. As shown by the changing water quality in this study, effluents should be monitored throughout the drainage period.

It was not the intent of this study to determine the long-term effects of re-using this water downstream. The effect of using or irrigating poor quality water is a subject that deserves more attention that can be provided in this text. However, it is known that saline water can be successfully used for irrigation in some circumstances. For example, Oosterveld (1978) reports that a single, 60 mm application of saline drainage water (EC = 9.34 mmhos/cm) was irrigated near Lethbridge, Alberta, without significantly increasing the salinity of the soil. The reader is referred to Saskatchewan Water Corporation (1987) and Steppuhn and Curtin (1993) for further discussion of the suitability of using this water for irrigation within the Canadian Prairies.

The results of this study also indicate that the installation of an artificial permeable material, such as gravel, around the drainage well and drain lines plays a large role in the hydraulic properties of the system. This is particularly true if the drainage system is being operated periodically as the large seepage face of the gravel filled trench aids in the water level recovery rate in the system after the valve is closed. Therefore, if the drainage system is to be operated in short, controlled events the installation of gravel surrounding the drain lines is recommended.

6. SUMMARY AND CONCLUSIONS

The intention of this research was to evaluate two types of subsurface drainage systems for lowering ground water tables in saline seeps and to develop recommendations for further use of this technology in the prairies. Performance evaluations were based on the ability of the drainage system to lower water tables, reduce soil salinity, and to provide water that was of a suitable quality so as to minimize the environmental risk associated with reuse or disposal. The two drainage systems evaluated were: (1) a traditional system[1], based on a design that is typically used in humid or irrigated areas and; (2) an experimental system that uses a smaller amount of precisely placed tubing and is valve controlled, allowing for the implementation of a water management plan. The two systems were installed into similar saline seeps termed the south parcel (traditional drainage treatment installed September 1990) and the north parcel (experimental drainage treatment installed September 1997). Climatic, hydrologic, geologic, and chemical data was used to characterize each parcel. Both parcels were monitored for hydrologic changes caused by the drainage systems.

Water level measurements were used to evaluate the effectiveness of each system at maintaining hydraulic control of the water table. South parcel and north parcel water table elevations (both parcels untreated) were found to be highly correlated ($r^2 = 0.87$).

[1] Research and evaluation of this system is ongoing by Agriculture and Agri-Food Canada personnel. Published results will be available when the evaluation is complete.

After installation of the traditional drainage system in the south parcel (north parcel still untreated) correlation was still high ($r^2 = 0.82$); however, the slope of the trend line had significantly changed ($\alpha = 0.05$). Since installation, the traditional drainage system has maintained an average water table depth of 1.78 m; approximately equal to drain depth. During the same time the untreated north parcel had an average water table depth of 1.23 m. Overall, the performance of the traditional system with respect to water table control was very good, continuously maintaining ground water levels below 1.5 m from the soil surface except for a few days following large precipitation events (> 25 mm).

The experimental system was operated periodically during 1998 and 1999 according to the demand of a down-slope trickle irrigation system. Once the drains were initially opened the average water table depth was lowered from approximately 1.0 m to 1.5 m (safe depth corresponding to minimal salinity hazard) in 9 days during 1998 and 10 days in 1999. However, late opening of the drain valves created an early salinity risk due to high water table in both years. These results indicate that, if operated in a continuous manner, the experimental drainage system would be equally as effective at lowering water tables as the traditional system.

Based on the sampling points used in this study, large bulk reductions in average soil salinity were not noticed in either parcel after the installation of their respective drainage systems. The average EC_e (0-90 cm) of the south parcel and north parcels were 93 % and 115 % of levels measured prior to drainage. In each parcel, the largest net reductions in soil salinity were noticed in the near surface depths, with the EC_e of the south parcel (0-45 cm) being reduced to 81 % of original levels and the EC_e of the north parcel (0-15 cm) being reduced to 75 % of original levels. Based on the information presented in this thesis, there is insufficient evidence to make any conclusive distinctions between the two systems with respect to the ability to lower soil salinity above the drain lines, although salinity reductions were observed in the near surface depths of each parcel. However, despite the lack of apparent reductions in total root-zone salinity, an acceptable crop was grown in the south parcel one year after installation of the traditional drainage system and has continued in every year since that time. Similarly, in the north parcel an acceptable crop was grown two years after the installation of the experimental drainage system.

Large differences in water quality were noticed between the effluent of the traditional and experimental drainage systems. Average discharge effluent EC values for the traditional system and the experimental system were 7.1 dS/m and 4.7 dS/m respectively. This difference in EC is attributed to segments of the traditional drainage system intersecting a highly saline bedrock layer.

At this site, both the traditional and experimental systems performed as they were designed. The traditional system performed better than the experimental system in terms of water table control. However, the inability of the experimental system to completely minimize the salinization hazard presented by high water tables was related to the water management plan rather than the physical ability of the drainage system. There was no evidence presented to suggest that either design is superior in terms of their ability to lower water tables or transport salts out of the soil profile. The water quality of the effluent produced by the experimental system was superior to that of the traditional system. This advantage can be attributed to a design objective of the experimental system to precisely place a relatively small amount of tubing based on a subsurface investigation, rather than attempting to cover the entire salinized area as the design of the traditional system had done. From the results presented in this study, in consideration of the reduced cost and installation effort, the experimental system is well suited to western Canada. It is roughly equal in performance to the traditional system yet is much more flexible, as it offers the landowner the option to use a water management plan.

Some of the recommendations for use of this technology in a semiarid climate include: adaptations to the water management plan to release water through the experimental drainage system earlier in the year; the use of an artificial, porous material if the drainage system is to be used to provide water "on-demand", and where the horizontal hydraulic conductivity is high, drainage systems do not have to be as laterally expansive as those used in humid or irrigated areas.

7. RECOMMENDATIONS FOR FUTURE WORK

In preparing this report, topics were revealed that would benefit from additional monitoring or investigation. Some of the identified topics that would provide heightened insight into the physical processes occurring at a site similar to the one presented in this report are:

- Increased knowledge of the vertical variation of the soil hydraulic conductivity at this site would provide insight into the applicability of transferring the results from this study to other areas.
- Soil sampling should be completed a number of times throughout the year so that crop growth can be related to the actual amount of salts present in the soil at a given time.
- The completion of a salt balance would reveal the effect of the drainage systems at removing salts from the soil profile. This would require soil sampling to the depth of the drains.

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APPENDICES

If further information is required upon the information contained within the appendices please refer to:

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APPENDIX A: EXPERIMENTAL SYSTEM DIMENSIONS

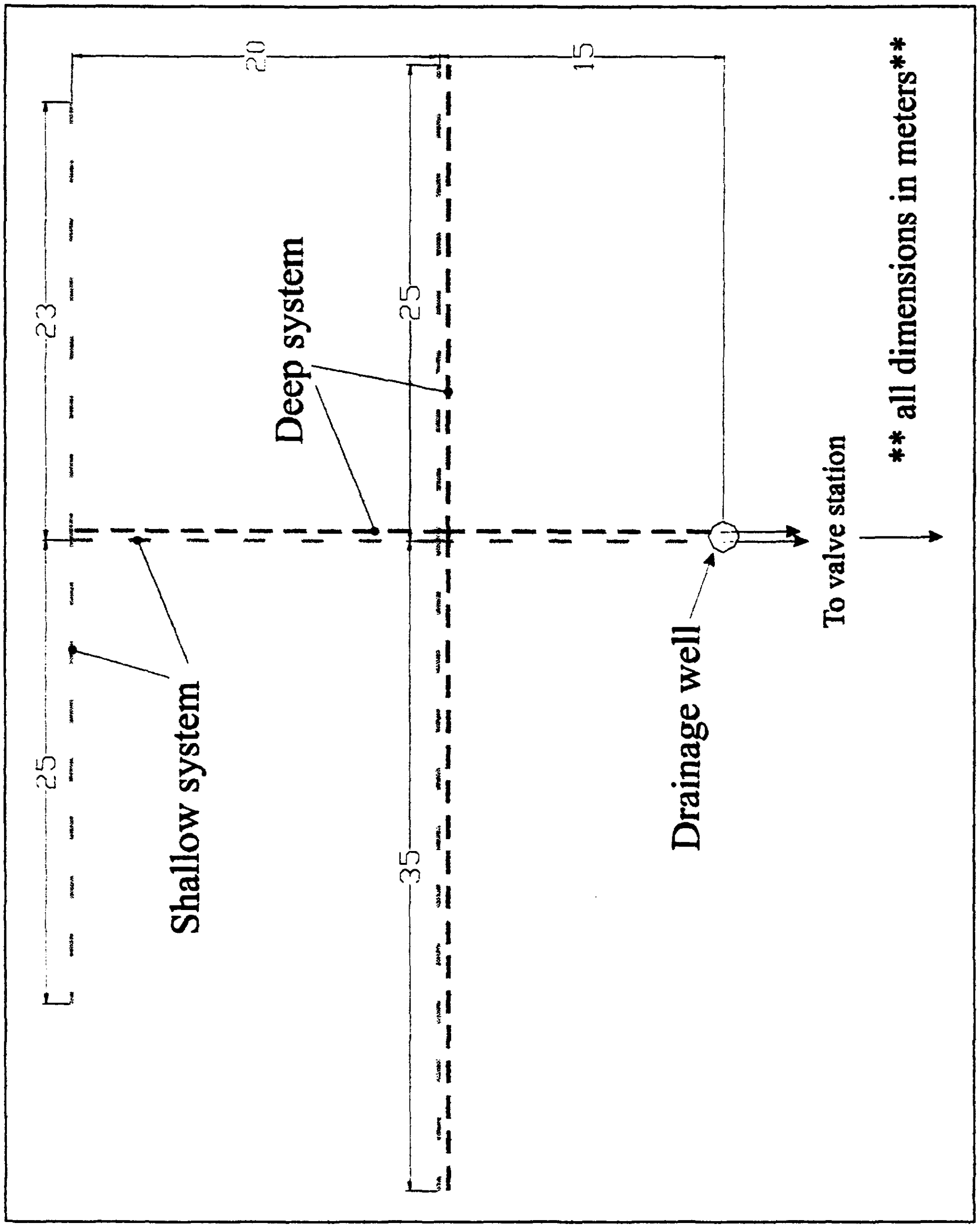

Figure A1: Plan view of experimental drainage system.

APPENDIX B: LOCATION OF SAMPLING POINTS

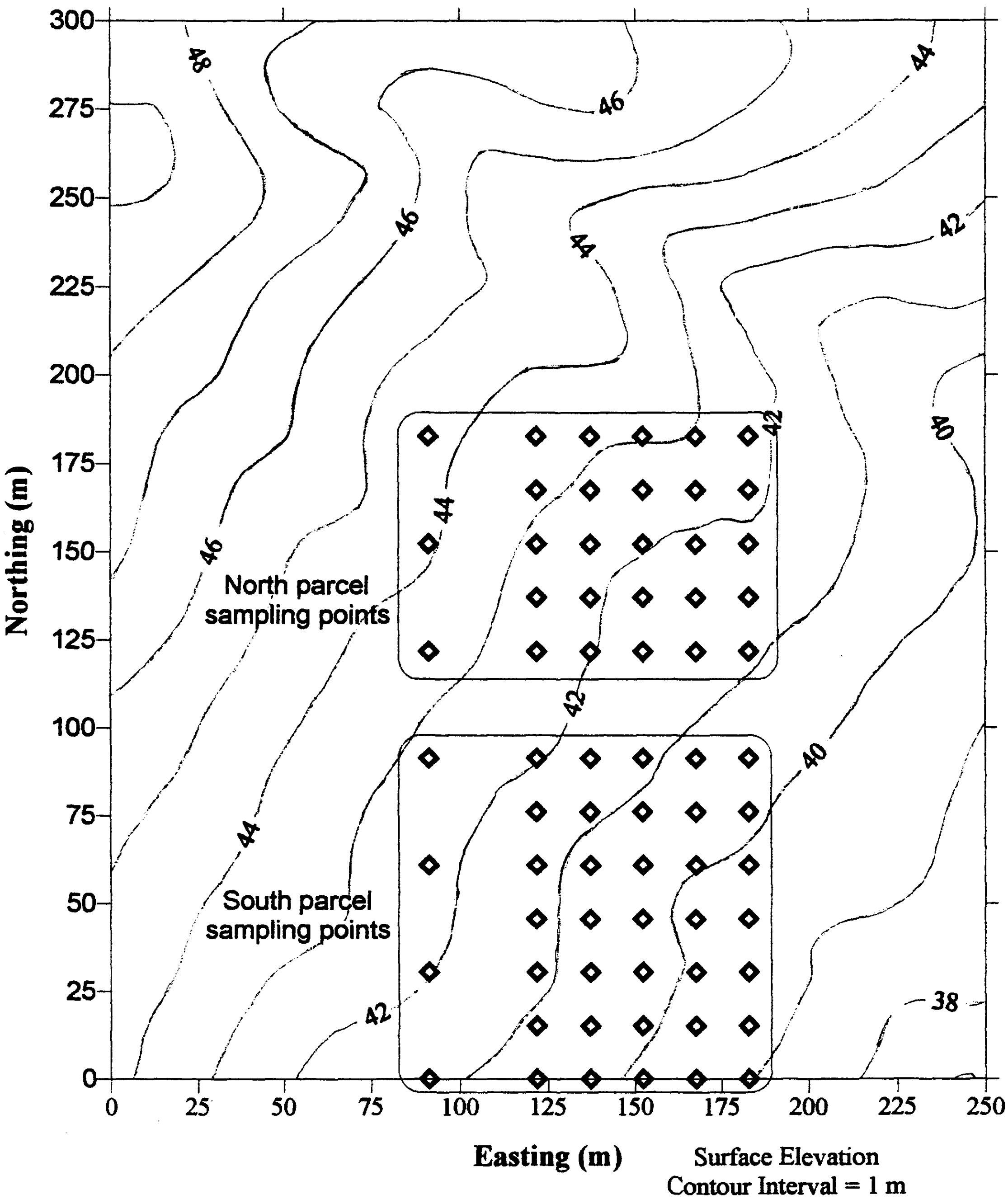

Figure B1: Location of soil sampling points used for initial site characterization.

APPENDIX C: PRECIPITATION, POTENTIAL EVAPOTRANSPIRATION AND TEMPERATURE DATA

Table C1: Mean monthly precipitation (mm) (SPARC weather station).

	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Jan	8.6	5.4	5.4	6.5	13.9	17.1	7.6	13.6	3.3	28.2	14.3	11.9	14.1	14.2	16.9
Feb	14.0	9.1	13.7	11.0	13.6	4.1	18.0	2.3	4.0	12.3	5.6	7.0	1.5	6.2	8.7
Mar	28.8	10.8	25.0	10.3	15.4	18.3	13.9	4.4	35.0	6.2	27.7	10.8	37.2	16.2	19.0
Apr	6.3	11.5	13.2	1.7	24.0	22.0	50.2	11.2	12.8	9.8	30.9	26.2	41.8	15.9	25.5
May	27.9	121.5	22.8	35.3	61.5	40.8	95.5	29.4	15.2	62.6	30.0	65.0	49.9	38.1	93.9
Jun	17.0	50.8	35.7	73.0	117.5	42.7	164.5	66.0	51.9	81.9	101.0	77.7	69.8	90.5	86.2
Jul	24.8	32.4	59.4	34.9	30.9	75.8	42.1	86.8	107.4	15.6	57.8	23.1	43.6	37.0	60.3
Aug	39.3	16.2	42.9	26.6	72.2	19.2	31.3	59.0	153.4	31.6	107.6	30.4	48.0	35.3	16.8
Sep	42.8	81.4	8.8	32.7	39.5	3.5	12.9	26.0	55.6	6.1	53.0	105.7	15.0	25.8	3.0
Oct	21.4	26.4	6.0	8.8	8.7	2.5	16.2	11.2	16.0	38.5	35.0	14.3	20.9	41.7	16.2
Nov	16.0	6.5	3.2	11.7	19.3	10.6	11.1	12.9	27.8	6.6	30.3	38.8	2.7	23.6	
Dec	21.2	7.5	8.6	30.7	11.6	22.3	11.2	18.3	8.0	3.1	36.4	30.7	0.2	25.5	
Total	268.1	379.5	244.7	283.2	428.1	278.9	474.5	341.1	490.4	302.5	529.6	441.6	344.7	370.0	

Table C2: Mean monthly temperature (deg. C) (SPARC weather station)

	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Jan	-11.8	-3.9	-5.0	-12.6	-10.0	-6.3	-12.4	-4.9	-14.2	-14.8	-10.8	-18.0	-16.0	-13.9	-12.3
Feb	-12.1	-11.5	-2.8	-9.0	-17.0	-8.5	-1.9	-3.3	-10.4	-16.8	-7.3	-8.1	-6.8	-1.9	-5.1
Mar	-1.9	2.2	-1.3	-0.3	-7.4	-0.4	-2.5	2.0	-1.2	0.8	-2.8	-8.0	-4.8	-3.8	-1.7
Apr	6.4	4.2	8.6	6.1	4.6	4.1	5.8	5.9	5.5	5.7	1.8	3.8	2.7	7.5	5.6
May	13.4	11.4	14.0	15.4	10.9	10.3	10.7	10.9	12.2	11.8	9.7	7.6	10.2	12.6	9.9
Jun	13.1	16.9	18.2	21.1	15.6	16.3	15.7	15.4	14.1	15.3	16.3	15.8	16.4	14.0	14.1
Jul	19.7	17.0	17.9	19.6	19.8	17.3	18.4	15.3	15.1	18.4	17.4	17.7	18.1	20.1	16.4
Aug	16.5	17.9	14.4	17.9	17.6	18.5	20.3	15.5	15.9	18.1	16.7	19.4	18.6	20.9	18.9
Sep	7.7	8.6	14.6	11.7	11.7	15.7	12.7	10.4	10.4	15.2	11.9	10.3	15.1	15.3	11.1
Oct	4.9	7.4	5.9	6.6	5.5	4.6	2.7	5.6	5.3	6.1	4.9	3.7	5.6	6.6	6.2
Nov	-13.7	-6.0	1.4	-3.0	-2.6	-4.2	-5.0	-1.9	-5.2	-2.6	-6.7	-10.0	-2.0	-0.9	
Dec	-9.5	-4.8	-5.3	-8.7	-10.4	-14.1	-5.6	-13.7	-6.1	-6.0	-12.3	-15.3	-3.2	-9.6	
Ave	2.7	5.0	6.7	5.4	3.2	4.4	4.9	4.8	3.5	4.3	3.2	1.6	4.5	5.6	

Table C3: Calculated potential evapotranspiration (PET) values (mm).

	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Apr	35.4	24.4	41.2	28.8	25.7	22.8	30.8	34.4	32.5	29.6	12.7	23.5	15.9	35.3	31.7
May	76.4	66.7	75.2	79.7	62.8	59.4	61.3	66.4	73.1	65.9	59.5	49.1	58.7	67.0	60.0
Jun	75.3	92.0	94.6	105.9	85.1	87.4	84.7	87.3	81.7	82.3	90.4	88.2	88.0	73.7	80.1
Jul	104.8	92.2	93.5	99.0	103.9	92.2	97.1	86.8	86.0	96.2	95.2	96.6	95.6	102.2	90.5
Aug	90.5	96.4	77.3	91.3	94.0	97.4	105.7	87.8	89.9	95.0	92.0	104.0	98.0	105.9	101.2
Sep	49.0	52.9	78.0	62.0	66.8	85.0	70.8	64.2	64.3	81.5	70.2	62.5	82.2	79.7	65.7
Oct	34.0	46.8	35.8	37.0	35.3	30.3	18.9	39.5	37.6	37.5	34.7	27.6	35.2	37.6	41.0

APPENDIX D: SOIL PROPERTIES

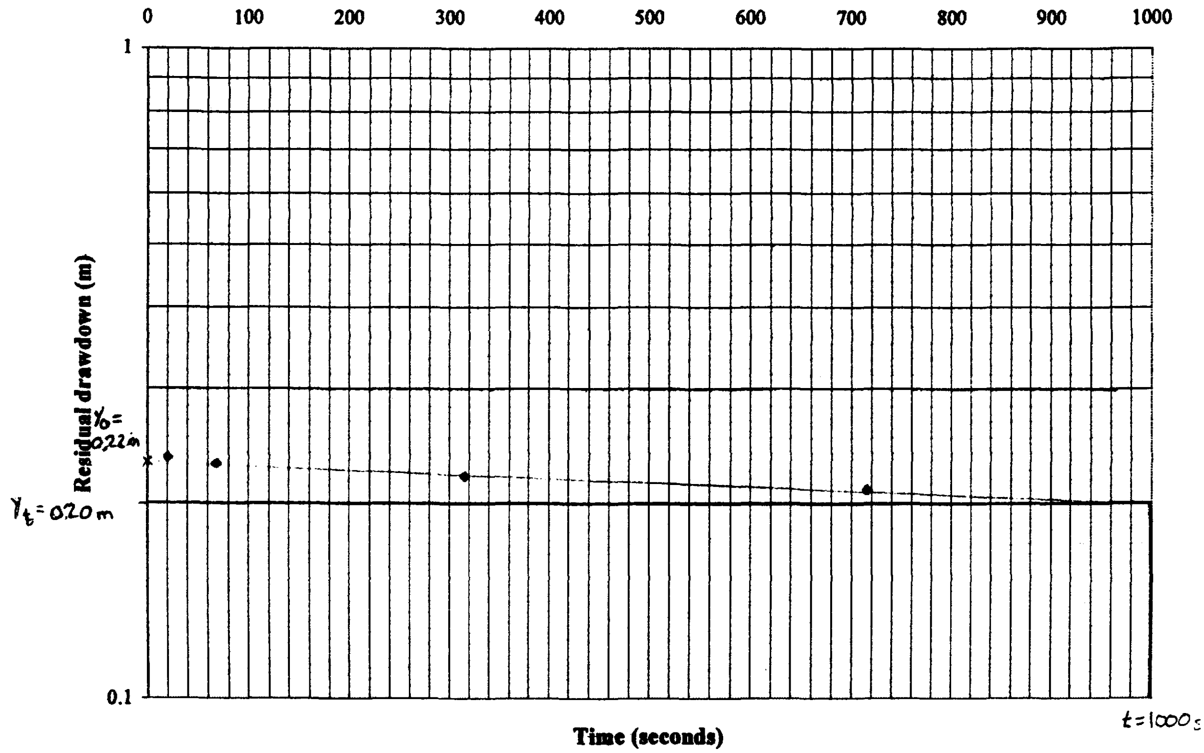

Figure D1: Slug test response – well 3020.

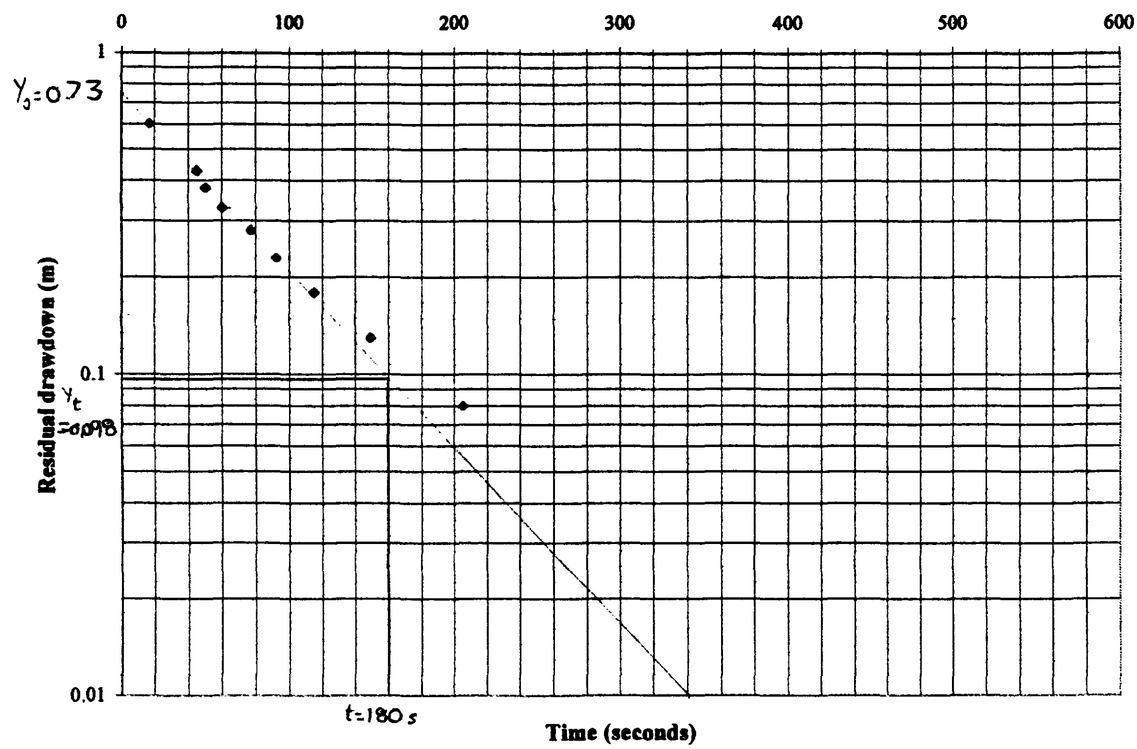

Figure D2: Slug test response – well 4020-1.

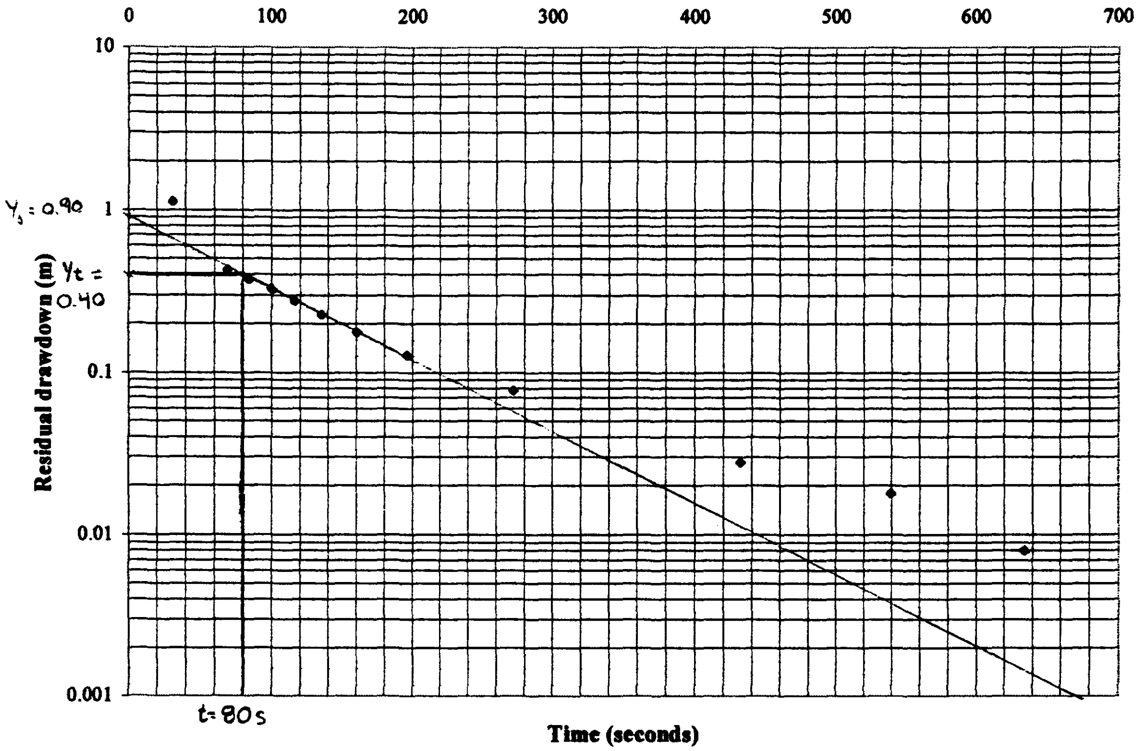

Figure D3: Slug test response – well 4020-2.

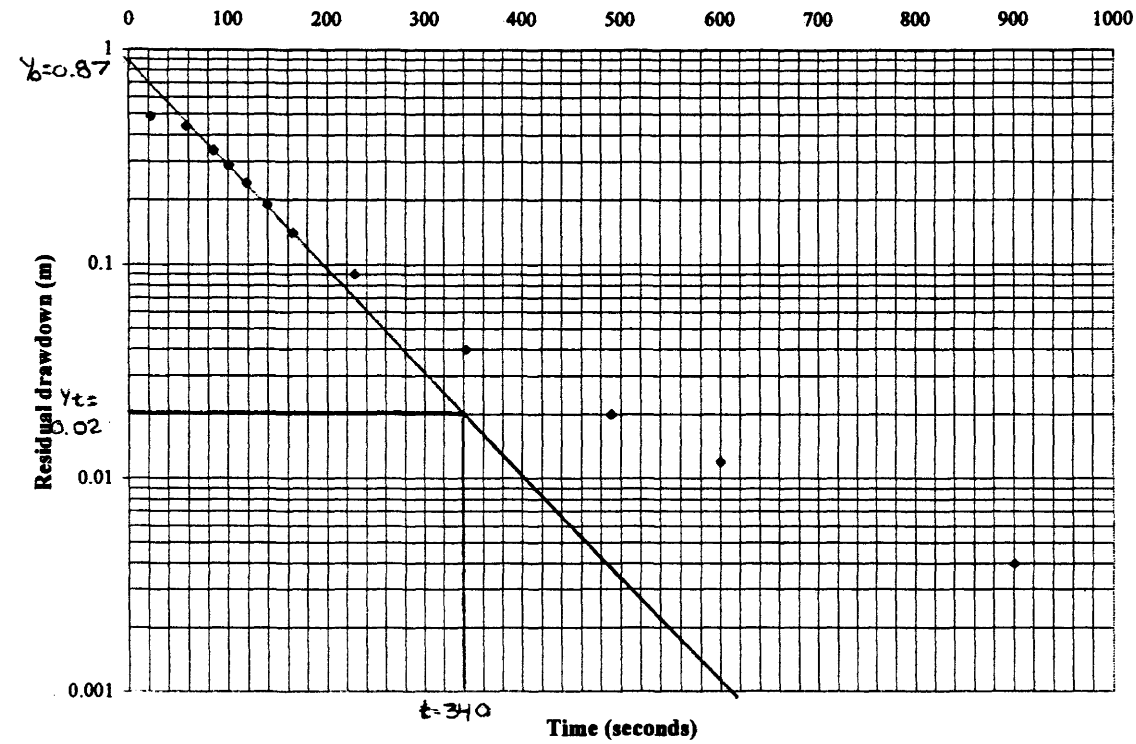

Figure D4: Slug test response – well 4020-3.

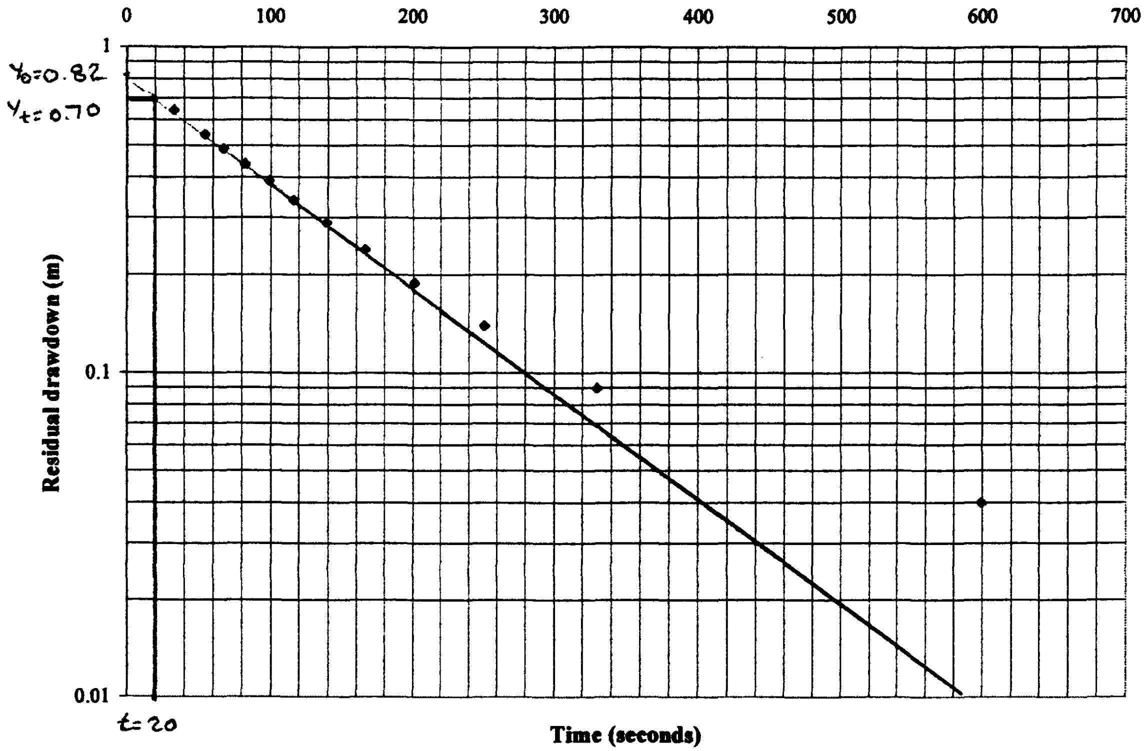

Figure D5: Slug test response – well 4520-1.

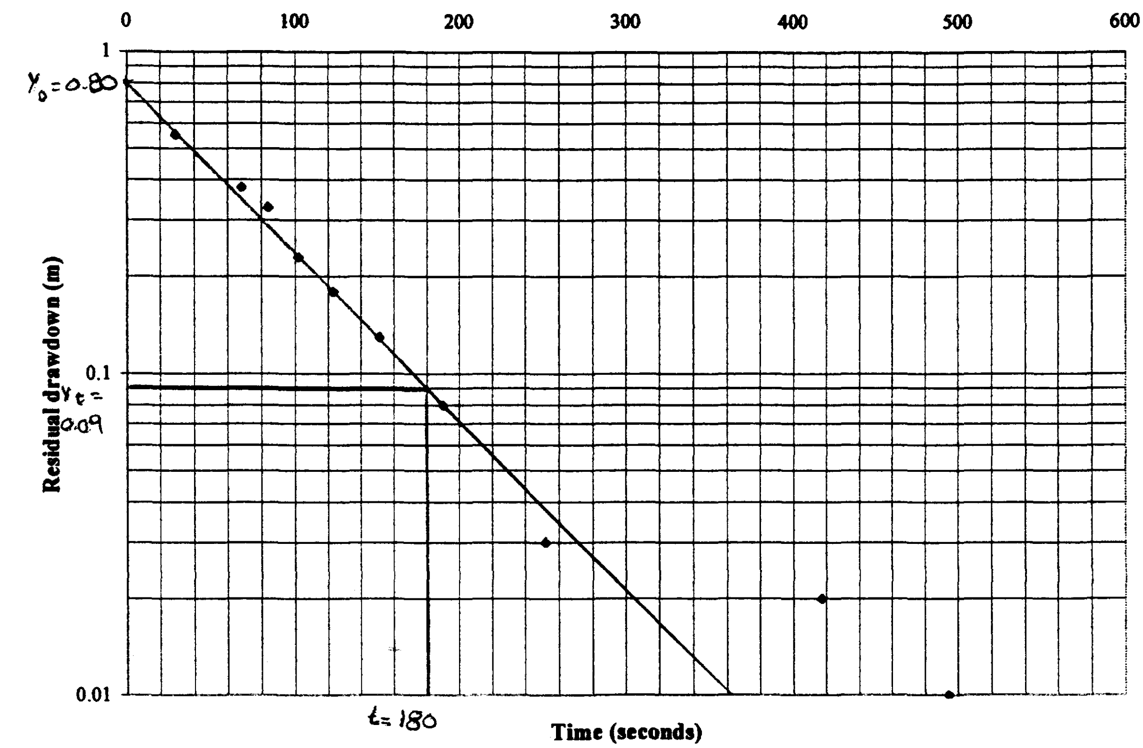

Figure D6: Slug test response – well 4520-2.

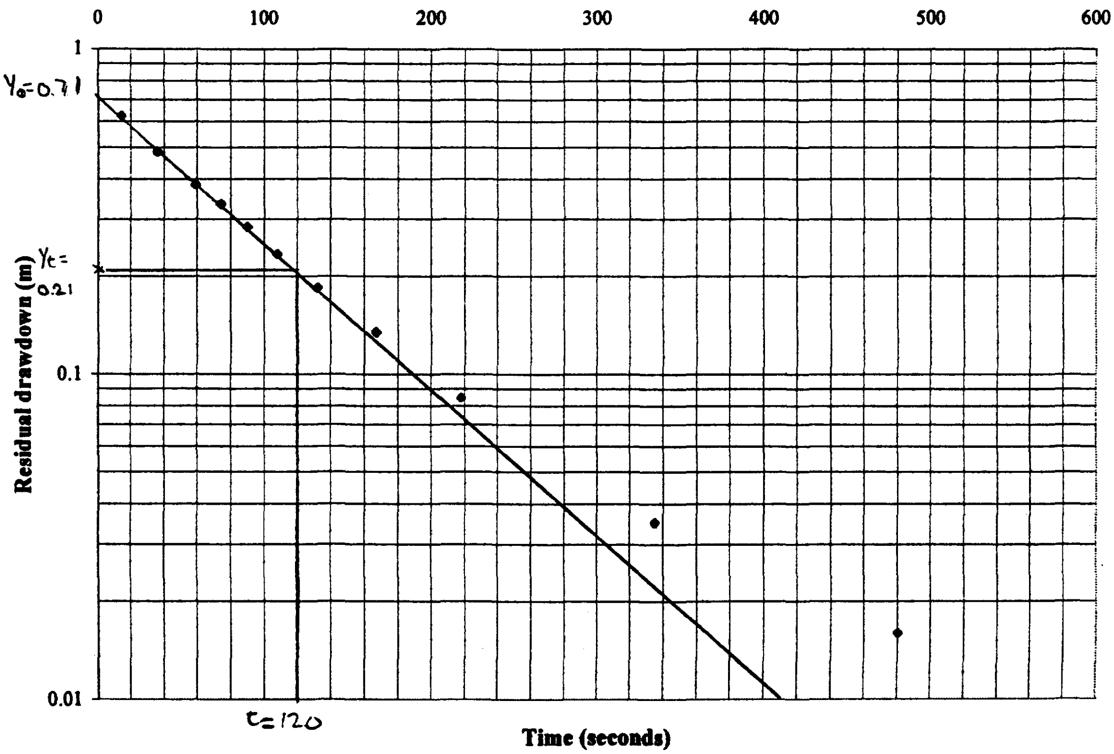

Figure D7: Slug test response – well 4520-3.

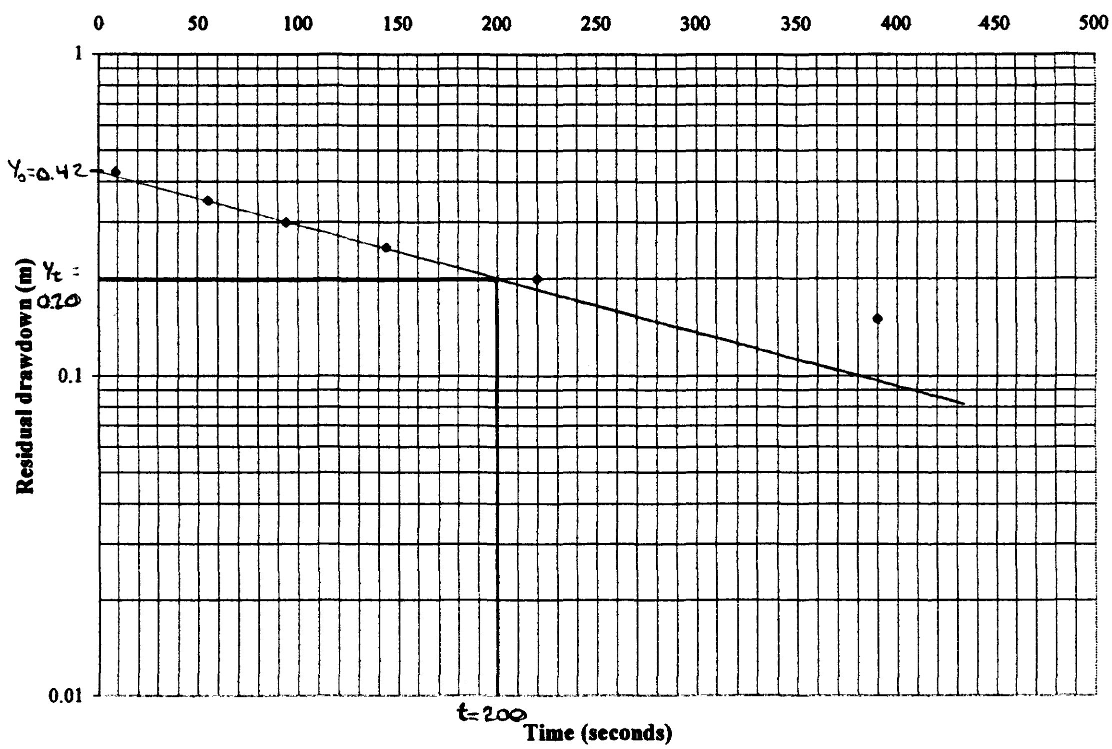

Figure D8: Slug test response – well 5025.

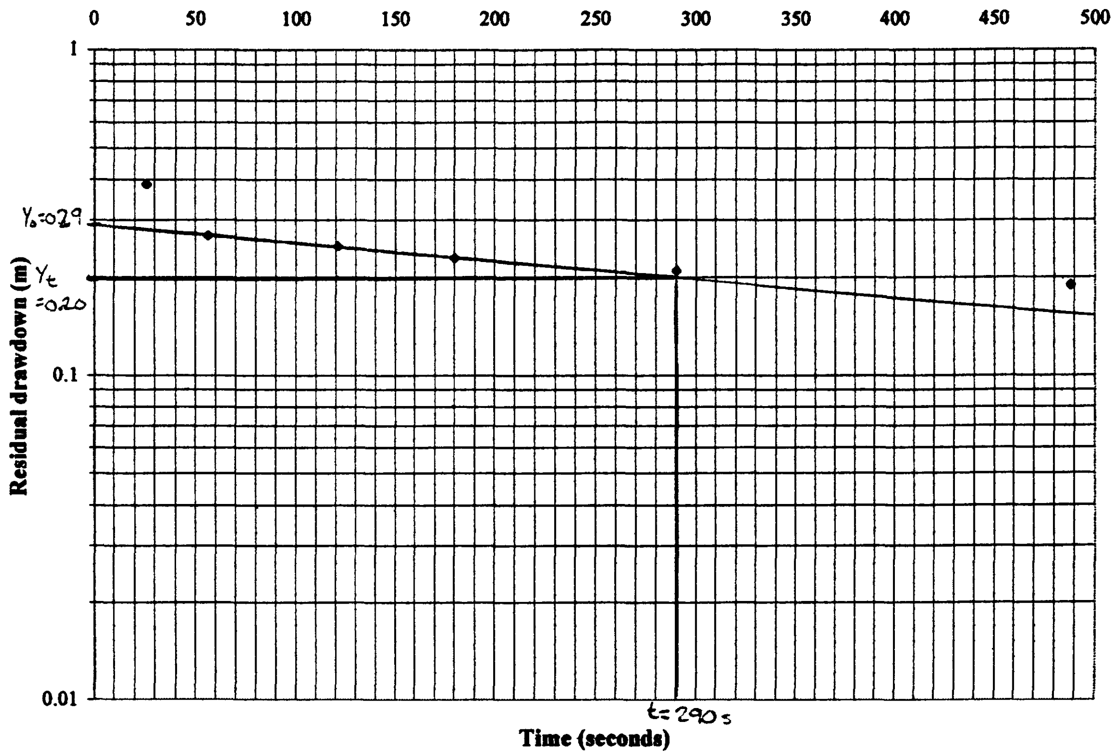

Figure D9: Slug test response – well 6020.

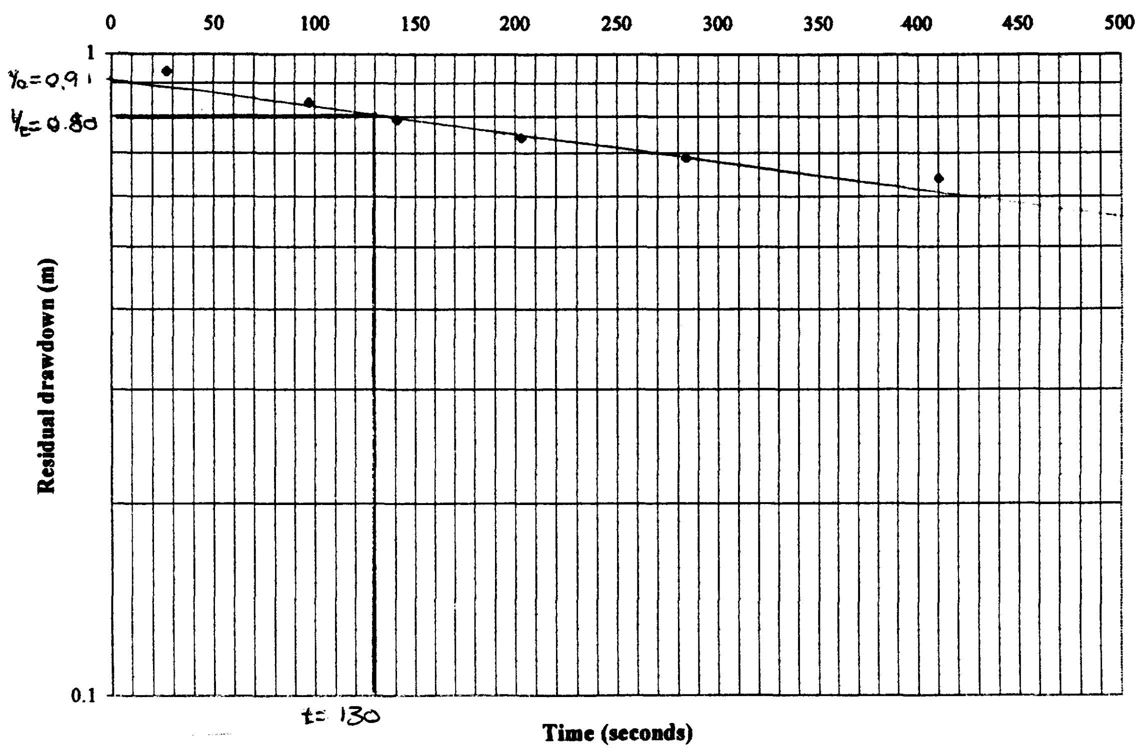

Figure D10: Slug test response – well 6520-1.

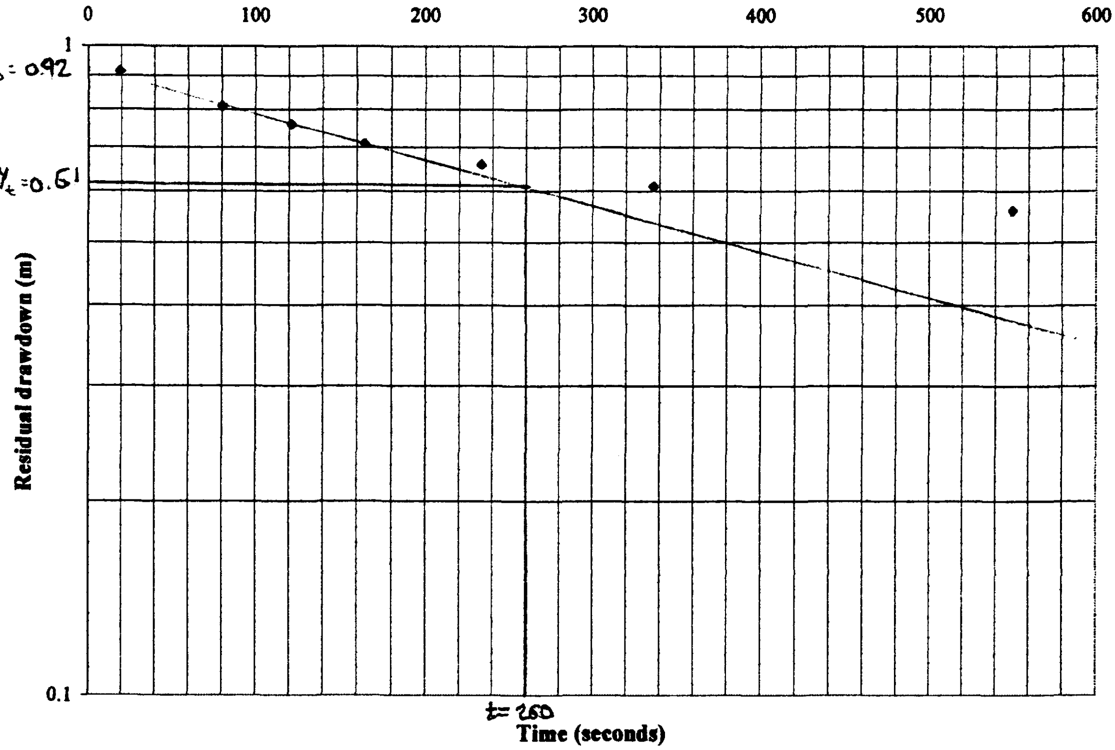

Figure D11: Slug test response – well 6520-2.

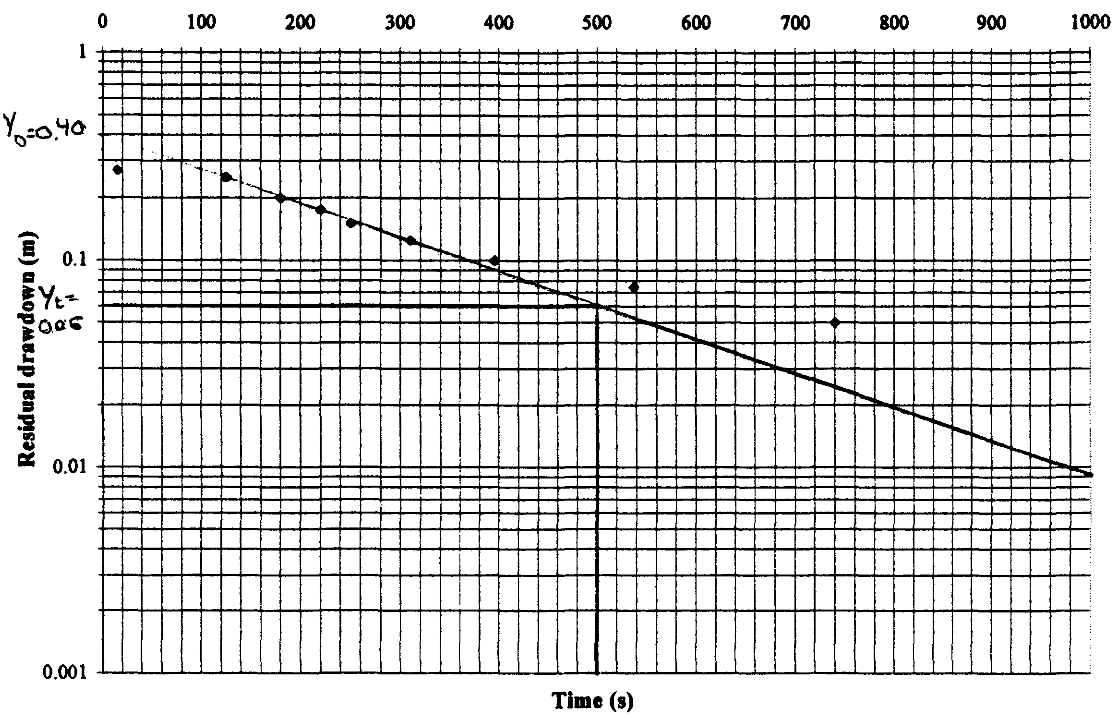

Figure D12: Slug test response – well 3050.

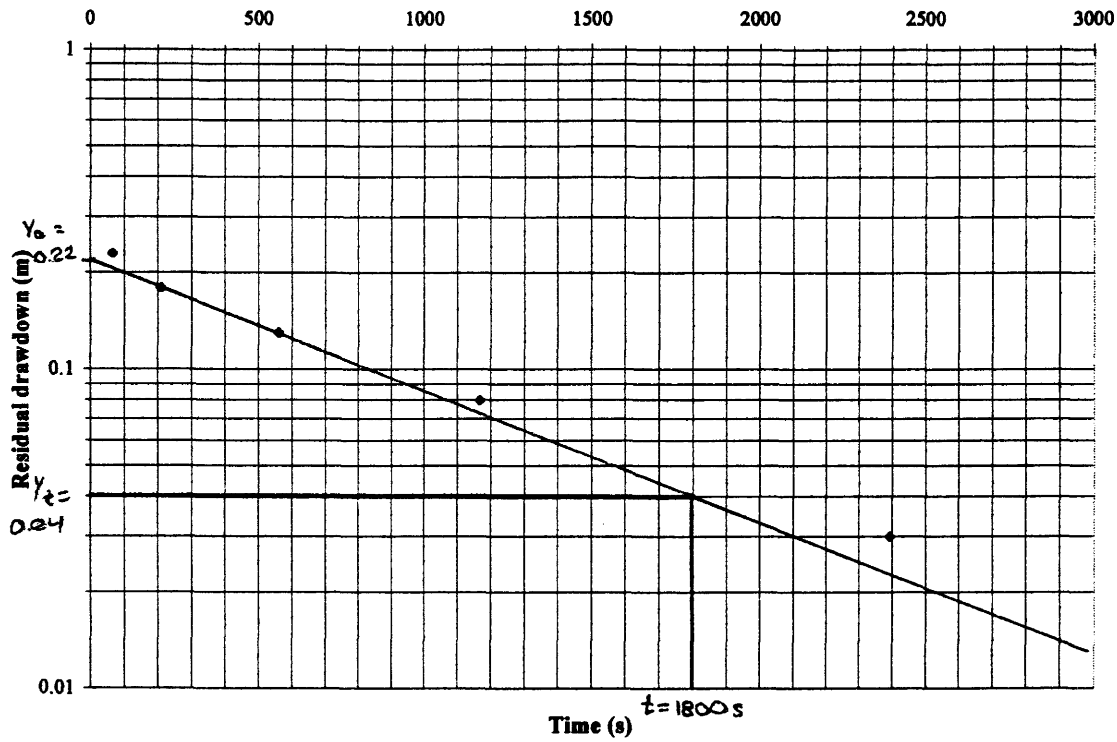

Figure D13: Slug test response – well 4050.

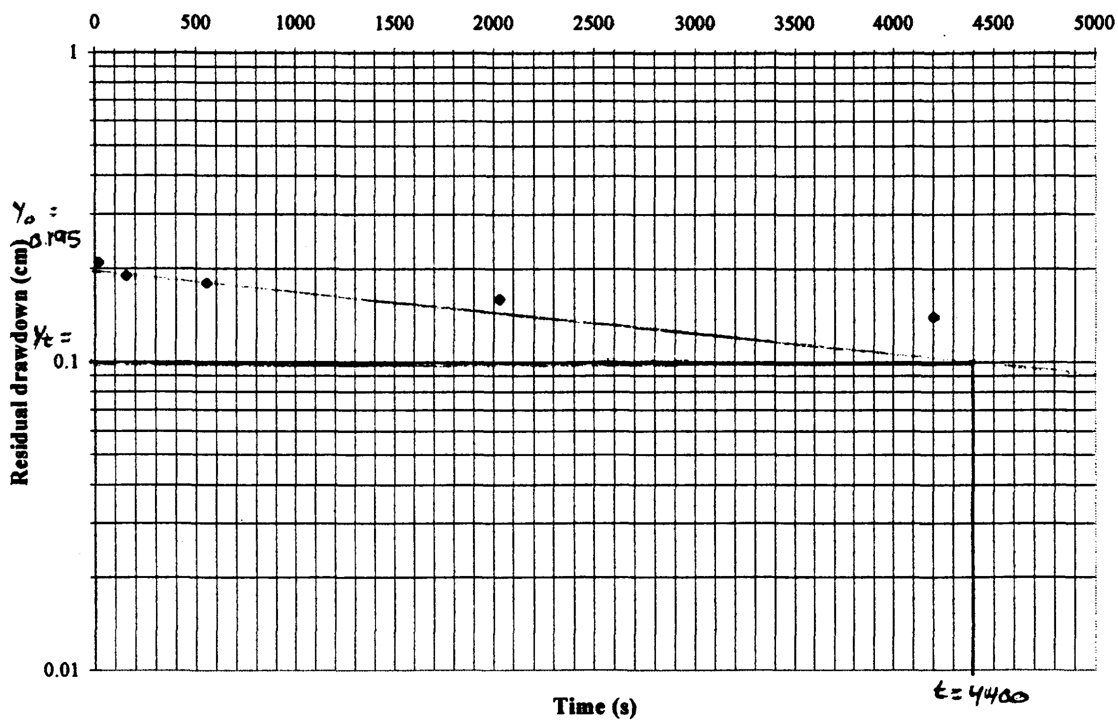

Figure D14: Slug test response – well 4550.

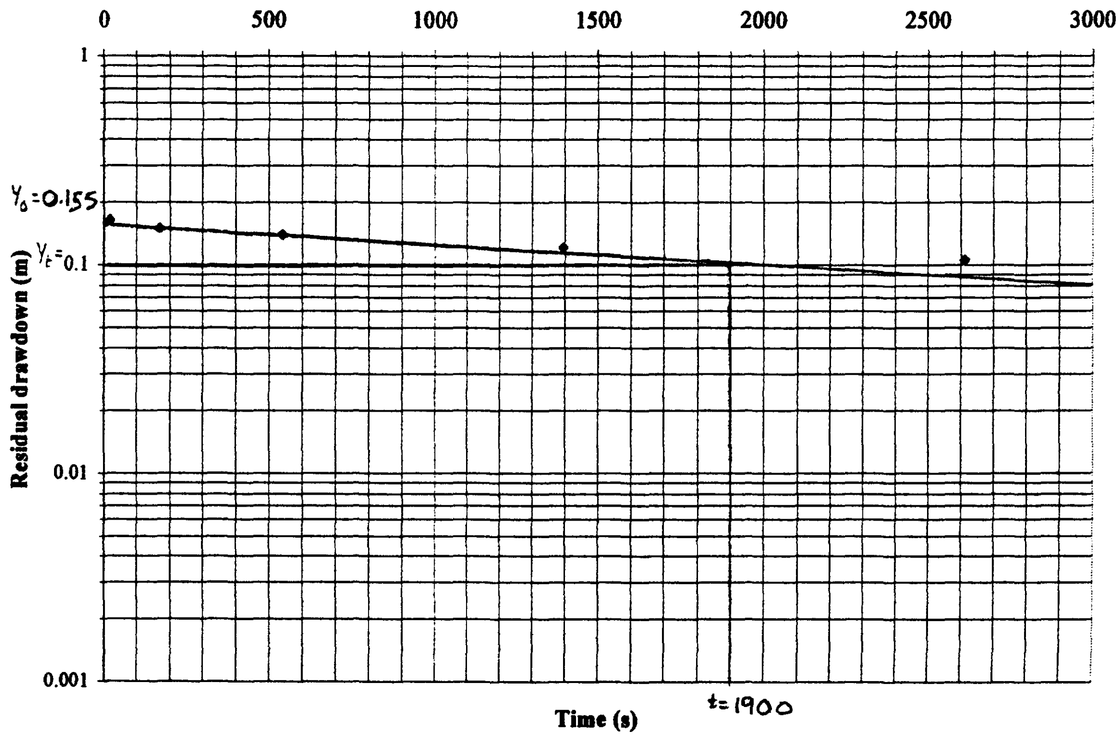

Figure D15: Slug test response – well 5050.

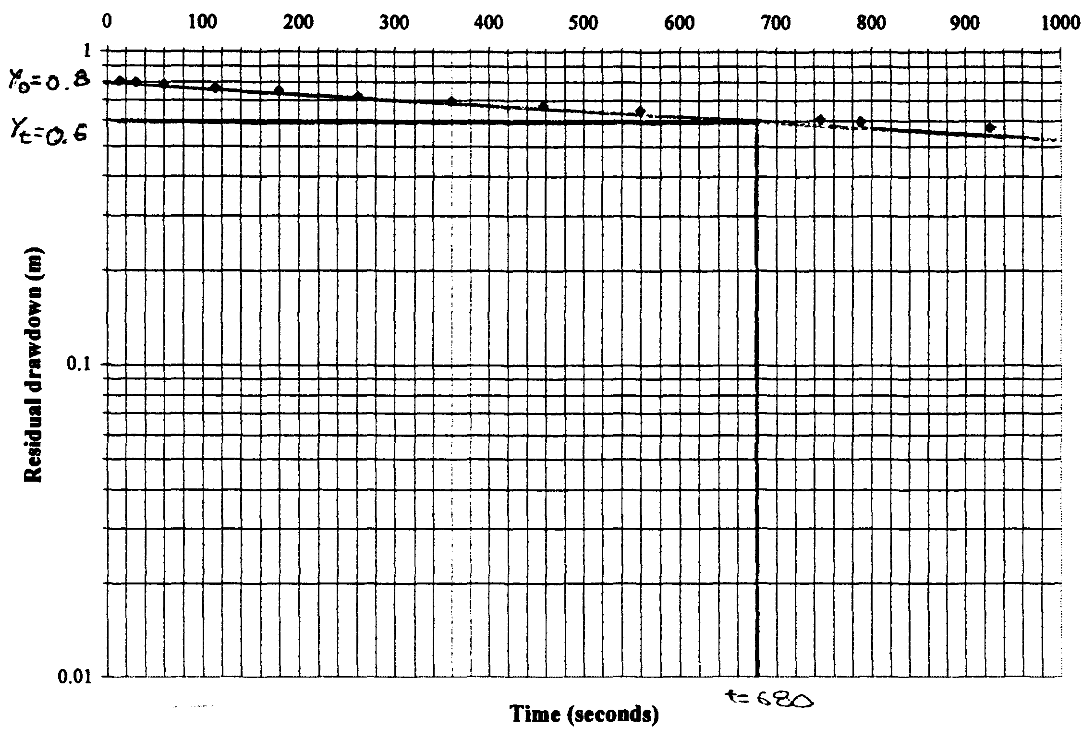

Figure D16: Slug test response – well 5550.

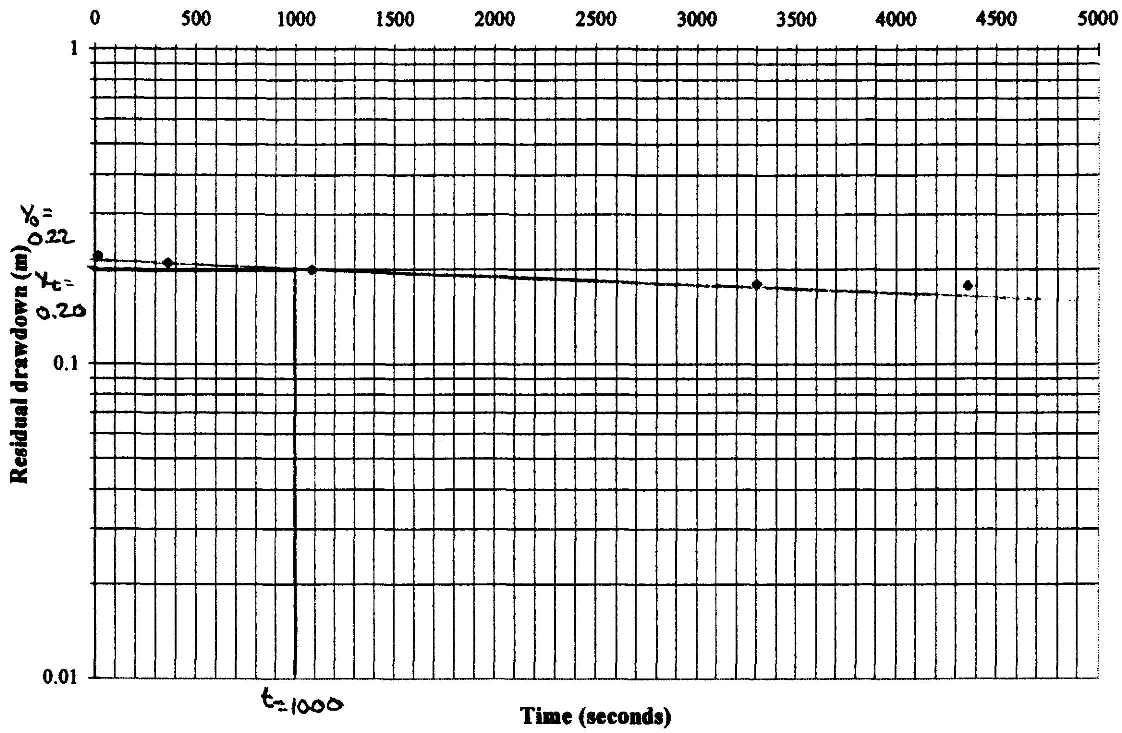

Figure D17: Slug test response – well 6050.

Table D1: Slug Test - Bouwer and Rice analysis - well 3020

Site	Smith Drainage		
Well ID	3020		
Well Location	300 E, 200 N		
equilibrium water level	EWL	1.84	
depth of water in well	H	0.35	
effective screen length	L	0.35	
height of w.l. over impermeable	D	3.66	
radius of auger hole	rw	0.0445	
inside radius of well casing	r1	0.0127	
outside radius of gravel pack	r2	0.0445	
porosity of gravel pack	h	0.3	
radius of porous region of well	rc	0.0265891	
*** all dimensions in meters			
l/rw	7.865168539		
ln[D-H/rw]	4.309214279	4.3092143	*** must not be larger than 6
A	1.8		
B	0.3		
ln[Re/rw] (if D > H)	1.079248446		
C	2		
ln[Re/rw] (if D = H)	1.269625977		
ln[Re/rw] (to be used in k calc)	1.079248446		
yo (m)	0.22		
t (sec.)	1000		
yt (m)	0.2		
(1/t)ln(yo/yt)	9.53102E-05		
Hydraulic Conductivity	1.04E-07	m/s	
	0.9	cm/day	
effective radius measured	0.130939795		

Table D2: Slug Test - Bouwer and Rice analysis - well 4020-1

Site	Smith Drainage	
Well ID	4020-1	
Well Location	400 E, 200 N	
equilibrium water level	EWL	1.76
depth of water in well	H	2.22
effective screen length	L	2.22
height of w.l. over impermeable	D	2.74
radius of auger hole	rw	0.0445
inside radius of well casing	r1	0.0127
outside radius of gravel pack	r2	0.0445
porosity of gravel pack	h	0.3
radius of porous region of well	rc	0.0265891
*** all dimensions in meters		

l/rw	49.88764045	
ln[D-H/rw]	2.458339622	2.4583396 *** must not be larger than 6
A	2.9	
B	0.5	
ln[Re/rw] (if D > H)	2.746380308	
C	2	
ln[Re/rw] (if D = H)	3.111036049	
ln[Re/rw] (to be used in k calc)	2.746380308	
yo (m)	0.73	
t (sec.)	180	
yt (m)	0.098	
(1/t)ln(yo/yt)	0.011155984	
Hydraulic Conductivity	4.88E-06	m/s
	42.2	cm/day
effective radius measured	0.693582016	

Table D3: Slug Test - Bouwer and Rice analysis - well 4020-2

Site	Smith Drainage	
Well ID	4020-2	
Well Location	400 E, 200 N	
equilibrium water level	EWL	2.062
depth of water in well	H	1.918
effective screen length	L	1.918
height of w.l. over impermeable	D	2.438
radius of auger hole	rw	0.0445
inside radius of well casing	r1	0.0127
outside radius of gravel pack	r2	0.0445
porosity of gravel pack	h	0.3
radius of porous region of well	rc	0.0265891
*** all dimensions in meters		

l/rw	43.1011236		
ln[D-H/rw]	2.458339622	2.4583396	*** must not be larger than 6
A	2.7		
B	0.9		
ln[Re/rw] (if D > H)	2.461516715		
C	0.5		
ln[Re/rw] (if D = H)	3.290795021		
ln[Re/rw] (to be used in k calc)	2.461516715		
yo (m)	0.9		
t (sec.)	80		
yt (m)	0.4		
(1/t)ln(yo/yt)	0.010136628		
Hydraulic Conductivity	4.60E-06	m/s	
	39.7	cm/day	
effective radius measured	0.521654715		

Table D4: Slug Test - Bouwer and Rice analysis - well 4020-3

Site	Smith Drainage	
Well ID	4020-3	
Well Location	400 E, 200 N	
equilibrium water level	EWL	2.05
depth of water in well	H	1.93
effective screen length	L	1.93
height of w.l. over impermeable	D	2.45
radius of auger hole	rw	0.0445
inside radius of well casing	r1	0.0127
outside radius of gravel pack	r2	0.0445
porosity of gravel pack	h	0.3
radius of porous region of well	rc	0.0265891
*** all dimensions in meters		

l/rw	43.37078652		
ln[D-H/rw]	2.458339622	2.4583396	*** must not be larger than 6
A	2.7		
B	0.5		
ln[Re/rw] (if D > H)	2.615140775		
C	2		
ln[Re/rw] (if D = H)	2.959387723		
ln[Re/rw] (to be used in k calc)	2.615140775		
yo (m)	0.87		
t (sec.)	340		
yt (m)	0.02		
(1/t)ln(yo/yt)	0.011096356		
Hydraulic Conductivity	5.31E-06	m/s	
	45.9	cm/day	
effective radius measured	0.608276753		

Table D5: Slug Test - Bouwer and Rice analysis - well 4520-1

Site	Smith Drainage		
Well ID	4520-1		
Well Location	450 E, 200 N		
equilibrium water level	EWL	1.865	
depth of water in well	H	2.22	
effective screen length	L	2.22	
height of w.l. over impermeable	D	2.385	
radius of auger hole	rw	0.0445	
inside radius of well casing	r1	0.0127	
outside radius of gravel pack	r2	0.0445	
porosity of gravel pack	h	0.3	
radius of porous region of well	rc	0.0265891	
*** all dimensions in meters			

l/rw	49.88764045		
ln[D-H/rw]	1.310456285	1.3104563	*** must not be larger than 6
A	2.9		
B	0.5		
ln[Re/rw] (if D > H)	2.835986842		
C	2		
ln[Re/rw] (if D = H)	3.111036049		
ln[Re/rw] (to be used in k calc)	2.835986842		
yo (m)	0.82		
t (sec.)	20		
yt (m)	0.7		
(1/t)ln(yo/yt)	0.0079112		
Hydraulic Conductivity	3.57E-06	m/s	
	30.9	cm/day	
effective radius measured	0.758601063		

Table D6: Slug Test - Bouwer and Rice analysis - well 4520-2

Site	Smith Drainage	
Well ID	4520-3	
Well Location	450 E, 200 N	
equilibrium water level	EWL	1.975
depth of water in well	H	2.11
effective screen length	L	2.11
height of w.l. over impermeable	D	2.275
radius of auger hole	rw	0.0445
inside radius of well casing	r1	0.0127
outside radius of gravel pack	r2	0.0445
porosity of gravel pack	h	0.3
radius of porous region of well	rc	0.0265891
*** all dimensions in meters		

l/rw	47.41573034	
ln[D-H/rw]	1.310456285	1.3104563 *** must not be larger than 6
A	2.8	
B	0.5	
ln[Re/rw] (if D > H)	2.793902786	
C	2	
ln[Re/rw] (if D = H)	3.055941175	
ln[Re/rw] (to be used in k calc)	2.793902786	
yo (m)	0.8	
t (sec.)	180	
yt (m)	0.09	
(1/t)ln(yo/yt)	0.012137789	
Hydraulic Conductivity	5.68E-06	m/s
	49.1	cm/day
effective radius measured	0.727338495	

Table D7: Slug Test - Bouwer and Rice analysis - well 4520-3

Site	Smith Drainage	
Well ID	4520-3	
Well Location	450 E, 200 N	
equilibrium water level	EWL	1.97
depth of water in well	H	2.115
effective screen length	L	2.115
height of w.l. over impermeable	D	2.28
radius of auger hole	rw	0.0445
inside radius of well casing	r1	0.0127
outside radius of gravel pack	r2	0.0445
porosity of gravel pack	h	0.3
radius of porous region of well	rc	0.0265891
*** all dimensions in meters		

l/rw	47.52808989		
ln[D-H/rw]	1.310456285	1.3104563	*** must not be larger than 6
A	2.8		
B	0.5		
ln[Re/rw] (if D > H)	2.796614051		
C	2		
ln[Re/rw] (if D = H)	3.058506296		
ln[Re/rw] (to be used in k calc)	2.796614051		
yo (m)	0.71		
t (sec.)	120		
yt (m)	0.21		
(1/t)ln(yo/yt)	0.010151312		
Hydraulic Conductivity	4.74E-06	m/s	
	41.0	cm/day	
effective radius measured	0.729313179		

Table D8: Slug Test - Bouwer and Rice analysis - well 5025

Site	Smith Drainage	
Well ID	5025	
Well Location	500 E, 250 N	
equilibrium water level	EWL	1.805
depth of water in well	H	0.74
effective screen length	L	0.74
height of w.l. over impermeable	D	1.695
radius of auger hole	rw	0.0445
inside radius of well casing	r1	0.0127
outside radius of gravel pack	r2	0.0445
porosity of gravel pack	h	0.3
radius of porous region of well	rc	0.0265891
*** all dimensions in meters		

l/rw	16.62921348		
ln[D-H/rw]	3.066222151	3.0662222	*** must not be larger than 6
A	1.7		
B	0.3		
ln[Re/rw] (if D > H)	1.822013218		
C	2		
ln[Re/rw] (if D = H)	1.954775586		
ln[Re/rw] (to be used in k calc)	1.822013218		
yo (m)	0.42		
t (sec.)	200		
yt (m)	0.2		
(1/t)ln(yo/yt)	0.003709687		
Hydraulic Conductivity	3.23E-06	m/s	
	27.9	cm/day	
effective radius measured	0.275201184		

Table D9: Slug Test - Bouwer and Rice analysis - well 6020

Site	Smith Drainage			
Well ID	6020			
Well Location	600 E, 200 N			
equilibrium water level	EWL	1.84		
depth of water in well	H	0.66		
effective screen length	L	0.66		
height of w.l. over impermeable	D	0.66		
radius of auger hole	rw	0.0445		
inside radius of well casing	r1	0.0127		
outside radius of gravel pack	r2	0.0445		
porosity of gravel pack	h	0.3		
radius of porous region of well	rc	0.0265891		
*** all dimensions in meters				
l/rw	14.83146067			
ln[D-H/rw]	#NUM!	#NUM!	*** must not be larger than 6	
A	1.7			
B	0.5			
ln[Re/rw] (if D > H)	#NUM!			
C	1.4			
ln[Re/rw] (if D = H)	1.990872891			
ln[Re/rw] (to be used in k calc)	1.990872891			
yo (m)	0.29			
t (sec.)	290			
yt (m)	0.2			
(1/t)ln(yo/yt)	0.001281254			
Hydraulic Conductivity	1.37E-06	m/s		
	11.8	cm/day		
effective radius measured	0.325825539			

Table D10: Slug Test - Bouwer and Rice analysis - well 6520-1

Site	Smith Drainage	
Well ID	6520-1	
Well Location	650 E, 200 N	
equilibrium water level	EWL	1.91
depth of water in well	H	0.59
effective screen length	L	0.59
height of w.l. over impermeable	D	0.59
radius of auger hole	rw	0.0445
inside radius of well casing	r1	0.0127
outside radius of gravel pack	r2	0.0445
porosity of gravel pack	h	0.3
radius of porous region of well	rc	0.0265891
*** all dimensions in meters		

l/rw	13.25842697		
ln[D-H/rw]	#NUM!	#NUM!	*** must not be larger than 6
A	1.7		
B	0.5		
ln[Re/rw] (if D > H)	#NUM!		
C	1.4		
ln[Re/rw] (if D = H)	1.882581507		
ln[Re/rw] (to be used in k calc)	1.882581507		
yo (m)	0.91		
t (sec.)	130		
yt (m)	0.8		
(1/t)ln(yo/yt)	0.000991022		
Hydraulic Conductivity	1.12E-06	m/s	
	9.7	cm/day	
effective radius measured	0.292384786		

Table D11: Slug Test - Bouwer and Rice analysis - well 6520-2

Site	Smith Drainage	
Well ID	6520-2	
Well Location	650 E, 200 N	
equilibrium water level	EWL	1.91
depth of water in well	H	0.31
effective screen length	L	0.31
height of w.l. over impermeable	D	0.31
radius of auger hole	rw	0.0445
inside radius of well casing	r1	0.0127
outside radius of gravel pack	r2	0.0445
porosity of gravel pack	h	0.3
radius of porous region of well	rc	0.0265891
*** all dimensions in meters		

l/rw	6.966292135		
ln[D-H/rw]	#NUM!	#NUM!	*** must not be larger than 6
A	1.7		
B	0.5		
ln[Re/rw] (if D > H)	#NUM!		
C	1		
ln[Re/rw] (if D = H)	1.407970191		
ln[Re/rw] (to be used in k calc)	1.407970191		
yo (m)	0.92		
t (sec.)	260		
yt (m)	0.61		
(1/t)ln(yo/yt)	0.001580441		
Hydraulic Conductivity	2.54E-06	m/s	
	21.9	cm/day	
effective radius measured	0.181900417		

Table D12: Slug Test - Bouwer and Rice analysis - well 3050

Site	Smith Drainage	
Well ID	3050	
Well Location	300 E, 500 N	

equilibrium water level	EWL	2.68	
depth of water in well	H	1.32	
effective screen length	L	1.32	
height of w.l. over impermeable	D	2.82	
radius of auger hole	rw	0.0445	
inside radius of well casing	r1	0.0127	
outside radius of gravel pack	r2	0.0445	
porosity of gravel pack	h	0.3	
radius of porous region of well	rc	0.0265891	
*** all dimensions in meters			

l/rw	29.66292135		
ln[D-H/rw]	3.517731198	3.5177312	*** must not be larger than 6
A	2.3		
B	0.4		
ln[Re/rw] (if D > H)	2.224854933		
C	2		
ln[Re/rw] (if D = H)	2.551555464		
ln[Re/rw] (to be used in k calc)	2.224854933		
yo (m)	0.4		
t (sec.)	500		
yt (m)	0.06		
(1/t)ln(yo/yt)	0.00379424		
Hydraulic Conductivity	2.26E-06	m/s	
	19.5	cm/day	
effective radius measured	0.411720253		

Table D13: Slug Test - Bouwer and Rice analysis - well 4050

Site	Smith Drainage		
Well ID	4050		
Well Location	400 E, 500 N		
equilibrium water level	EWL	2.105	
depth of water in well	H	2.095	
effective screen length	L	2.095	
height of w.l. over impermeable	D	2.395	
radius of auger hole	rw	0.0445	
inside radius of well casing	r1	0.0127	
outside radius of gravel pack	r2	0.0445	
porosity of gravel pack	h	0.3	
radius of porous region of well	rc	0.0265891	
*** all dimensions in meters			
l/rw	47.07865169		
ln[D-H/rw]	1.908293285	1.9082933	*** must not be larger than 6
A	3		
B	0.5		
ln[Re/rw] (if D > H)	2.705850718		
C	2		
ln[Re/rw] (if D = H)	3.048209773		
ln[Re/rw] (to be used in k calc)	2.705850718		
yo (m)	0.22		
t (sec.)	1800		
yt (m)	0.04		
(1/t)ln(yo/yt)	0.000947082		
Hydraulic Conductivity	4.32E-07	m/s	
	3.7	cm/day	
effective radius measured	0.666033459		

Table D14: Slug Test - Bouwer and Rice analysis - well 4550

Site	Smith Drainage	
Well ID	4550	
Well Location	450 E, 500 N	
equilibrium water level	EWL	2.14
depth of water in well	H	0.56
effective screen length	L	1.86
height of w.l. over impermeable	D	2.395
radius of auger hole	rw	0.0445
inside radius of well casing	r1	0.0127
outside radius of gravel pack	r2	0.0445
porosity of gravel pack	h	0.3
radius of porous region of well	rc	0.0265891
*** all dimensions in meters		

l/rw	41.79775281	
ln[D-H/rw]	3.719310571	3.7193106 *** must not be larger than 6
A	2.7	
B	0.45	
ln[Re/rw] (if D > H)	1.85528156	
C	2	
ln[Re/rw] (if D = H)	2.073777297	
ln[Re/rw] (to be used in k calc)	1.85528156	
yo (m)	0.195	
t (sec.)	4400	
yt (m)	0.1	
(1/t)ln(yo/yt)	0.000151779	
Hydraulic Conductivity	5.35E-08	m/s
	0.5	cm/day
effective radius measured	0.284510668	

Table D15: Slug Test - Bouwer and Rice analysis - well 5050

Site	Smith Drainage		
Well ID	5050		
Well Location	500 E, 500 N		
equilibrium water level	EWL	2.115	
depth of water in well	H	0.585	
effective screen length	L	0.585	
height of w.l. over impermeable	D	1.385	
radius of auger hole	rw	0.0445	
inside radius of well casing	r1	0.0127	
outside radius of gravel pack	r2	0.0445	
porosity of gravel pack	h	0.3	
radius of porous region of well	rc	0.0265891	
*** all dimensions in meters			
l/rw	13.14606742		
ln[D-H/rw]	2.889122538	2.8891225	*** must not be larger than 6
A	1.8		
B	0.25		
ln[Re/rw] (if D > H)	1.615863661		
C	2		
ln[Re/rw] (if D = H)	1.726712955		
ln[Re/rw] (to be used in k calc)	1.615863661		
yo (m)	0.165		
t (sec.)	1900		
yt (m)	0.1		
(1/t)ln(yo/yt)	0.000263566		
Hydraulic Conductivity	2.57E-07	m/s	
	2.2	cm/day	
effective radius measured	0.223934332		

Table D16: Slug Test - Bouwer and Rice analysis - well 5550

Site	Smith Drainage		
Well ID	5550		
Well Location	550 E, 500 N		
equilibrium water level	EWL	1.635	
depth of water in well	H	1.065	
effective screen length	L	1.065	
height of w.l. over impermeable	D	1.065	
radius of auger hole	rw	0.0445	
inside radius of well casing	r1	0.0127	
outside radius of gravel pack	r2	0.0445	
porosity of gravel pack	h	0.3	
radius of porous region of well	rc	0.0265891	
*** all dimensions in meters			

l/rw	23.93258427		
ln[D-H/rw]	#NUM!	#NUM!	*** must not be larger than 6
A	2.3		
B	0.4		
ln[Re/rw] (if D > H)	#NUM!		
C	1.7		
ln[Re/rw] (if D = H)	2.395420304		
ln[Re/rw] (to be used in k calc)	2.395420304		
yo (m)	0.8		
t (sec.)	680		
yt (m)	0.6		
(1/t)ln(yo/yt)	0.000423062		
Hydraulic Conductivity	3.36E-07	m/s	
	2.9	cm/day	
effective radius measured	0.488290001		

Table D17: Slug Test - Bouwer and Rice analysis - well 6050

Site	Smith Drainage		
Well ID	6050		
Well Location	600 E, 500 N		
equilibrium water level	EWL	1.815	
depth of water in well	H	1.085	
effective screen length	L	1.085	
height of w.l. over impermeable	D	1.085	
radius of auger hole	rw	0.0445	
inside radius of well casing	r1	0.0127	
outside radius of gravel pack	r2	0.0445	
porosity of gravel pack	h	0.3	
radius of porous region of well	rc	0.0265891	
*** all dimensions in meters			
l/rw	24.38202247		
ln[D-H/rw]	#NUM!	#NUM!	*** must not be larger than 6
A	2.3		
B	0.4		
ln[Re/rw] (if D > H)	#NUM!		
C	1.7		
ln[Re/rw] (if D = H)	2.414666635		
ln[Re/rw] (to be used in k calc)	2.414666635		
yo (m)	0.22		
t (sec.)	1000		
yt (m)	0.2		
(1/t)ln(yo/yt)	9.53102E-05		
Hydraulic Conductivity	7.50E-08	m/s	
	0.6	cm/day	
effective radius measured	0.497778811		

Table D18: Initial site characterization - percent sand sized particles.

South	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75.90*	*105-120*	*135-150*	*165-180*
Mean	33.40	27.98	21.49	24.03	28.83	33.61	35.54	36.77	40.13	44.00
Standard Deviation	4.35	6.80	7.33	7.36	11.03	10.58	8.02	6.60	9.43	14.47
Minimum	25.60	15.80	11.20	11.00	7.40	10.80	10.80	11.00	20.80	12.80
Maximum	38.80	44.20	40.80	40.80	50.20	50.80	49.20	45.60	56.40	60.40
Count	13	39	37	39	39	38	39	34	33	30
CV (%)	13.04	24.32	34.10	30.64	38.26	31.50	22.57	17.95	23.50	32.90

North	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75.90*	*105-120*	*135-150*	*165-180*
Mean	35.63	32.69	28.90	30.59	34.13	35.26	36.97	37.23	40.56	40.23
Standard Deviation	4.23	9.53	6.90	7.69	8.20	7.70	6.17	7.31	6.75	8.17
Minimum	28.60	10.80	16.60	13.80	14.40	8.60	13.60	17.40	21.40	16.80
Maximum	40.40	56.00	42.40	44.60	49.60	43.80	43.20	54.20	53.00	55.80
Count	14	28	28	28	28	27	27	25	23	19
CV (%)	11.86	29.15	23.87	25.12	24.02	21.84	16.69	19.63	16.65	20.31

T-test	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75.90*	*105-120*	*135-150*	*165-180*
s_p	4.29	8.05	7.15	7.50	9.95	9.50	7.33	6.91	8.44	12.44
t	-1.35	-2.36	-4.14	-3.53	-2.15	-0.69	-0.78	-0.25	-0.19	1.03
d.o.f.	25	65	63	65	65	63	64	57	54	47
t critical (ABS)	0.85	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.84
Difference α=0.05	**s.d.**	**s.d.**	**s.d.**	**s.d.**	**s.d.**	**s.d.**	**s.d.**	**n.s.d.**	**n.s.d.**	**s.d.**

Table D19: Initial site characterization - percent clay sized particles.

South	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75.90*	*105-120*	*135-150*	*165-180*
Mean	27.71	31.92	38.62	39.47	41.07	37.55	36.44	38.86	38.08	38.92
Standard Deviation	2.98	4.22	6.20	5.81	6.75	5.80	5.45	5.36	6.27	9.75
Minimum	23.40	23.60	25.40	28.40	30.20	25.20	23.20	20.80	23.80	23.60
Maximum	33.20	40.60	53.40	53.60	55.40	50.40	46.80	55.80	52.60	61.00
Count	13	39	37	39	39	38	39	34	33	30
CV (%)	10.77	13.22	16.05	14.71	16.43	15.44	14.95	13.80	16.46	25.05

North	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75.90*	*105-120*	*135-150*	*165-180*
Mean	28.46	33.66	38.82	41.31	41.66	41.61	40.96	40.41	35.53	33.99
Standard Deviation	3.87	6.46	5.38	6.07	5.71	6.24	5.81	5.05	6.31	10.07
Minimum	24.20	24.80	24.20	29.40	30.80	33.40	34.80	32.40	22.00	14.60
Maximum	37.80	48.20	52.20	60.80	57.60	65.40	62.40	54.60	52.60	57.60
Count	14	28	28	28	28	27	27	25	23	19
CV (%)	13.61	19.18	13.87	14.69	13.70	15.01	14.20	12.50	17.77	29.63

T-test	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75.90*	*105-120*	*135-150*	*165-180*
s_p	3.47	5.27	5.86	5.92	6.34	5.99	5.60	5.24	6.29	9.87
t	-0.56	-1.33	-0.14	-1.26	-0.37	-2.70	-3.22	-1.12	1.49	1.70
d.o.f.	25	65	63	65	65	63	64	57	54	47
t critical (ABS)	0.85	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.84
Difference α=0.05	**n.s.d.**	**s.d.**	**n.s.d.**	**s.d.**	**n.s.d.**	**s.d.**	**s.d.**	**s.d.**	**s.d.**	**s.d.**

Table D20: Initial site characterization - bulk density (g/m^3)

South Parcel	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75-90*	*105-120*	*135-150*	*165-180*
Mean	0.96	1.36	1.40	1.40	1.46	1.56	1.57	1.60	1.46	1.34
Standard Deviation	0.14	0.11	0.15	0.14	0.15	0.12	0.12	0.13	0.15	0.14
Minimum	0.54	1.08	1.01	1.05	1.04	1.28	1.30	1.17	1.20	1.09
Maximum	1.34	1.55	1.63	1.69	1.70	1.80	1.80	1.77	1.73	1.64
Count	36	33	34	32	33	28	29	23	23	25
CV (%)	14.47	8.36	10.80	10.29	10.09	7.57	7.45	8.09	10.38	10.41

North Parcel	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75-90*	*105-120*	*135-150*	*165-180*
Mean	0.94	1.41	1.49	1.50	1.54	1.61	1.64	1.72	1.68	1.55
Standard Deviation	0.20	0.10	0.11	0.12	0.14	0.12	0.14	0.16	0.09	0.18
Minimum	0.51	1.11	1.24	1.24	1.16	1.41	1.30	1.42	1.44	1.21
Maximum	1.40	1.60	1.71	1.73	1.71	1.80	1.84	2.06	1.79	1.83
Count	28	27	26	26	23	26	23	17	17	14
CV (%)	20.96	7.21	7.58	8.26	8.82	7.42	8.26	9.56	5.41	11.84

T-test										
s_p	0.17	0.11	0.14	0.14	0.14	0.12	0.13	0.14	0.13	0.16
t	0.58	-1.82	-2.50	-2.81	-1.89	-1.34	-2.05	-2.57	-5.33	-4.08
d.o.f.	62	58	58	56	54	52	50	38	38	37
t critical (ABS)	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.84	0.84	0.84
Difference a=0.05	n.s.d.	s.d.	s.d.	s.d.	s.d.	s.d.	s.d.	s.d.	s.d.	s.d.

Table D21: Initial site characterization - saturated soil paste extract pH.

South	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75-90*	*105-120*	*135-150*	*165-180*
Mean	7.51	7.71	8.06	8.24	8.26	8.15	8.05	7.79	7.46	7.10
Standard Deviation	0.29	0.34	0.31	0.24	0.17	0.14	0.14	0.28	0.66	1.09
Minimum	6.97	6.99	7.40	7.71	7.84	7.85	7.81	6.37	4.53	4.25
Maximum	7.97	8.22	8.57	8.63	8.53	8.45	8.39	8.13	8.04	8.04
Count	34.00	39.00	39.00	37.00	39.00	39.00	38.00	34.00	33.00	31.00
CV (%)	3.88	4.38	3.89	2.96	2.03	1.72	1.69	3.57	8.88	15.31

North	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75-90*	*105-120*	*135-150*	*165-180*
Mean	7.59	7.92	8.17	8.31	8.25	8.12	7.99	7.92	7.83	7.86
Standard Deviation	0.25	0.16	0.18	0.23	0.26	0.26	0.23	0.20	0.22	0.22
Minimum	7.05	7.42	7.69	7.75	7.65	7.61	7.54	7.61	7.12	7.32
Maximum	7.88	8.22	8.48	8.58	8.62	8.51	8.49	8.39	8.20	8.19
Count	19.00	28.00	28.00	28.00	27.00	27.00	27.00	25.00	23.00	19.00
CV (%)	3.24	2.07	2.22	2.81	3.16	3.26	2.93	2.52	2.79	2.85

T-test	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75-90*	*105-120*	*135-150*	*165-180*
s_p	0.28	0.28	0.27	0.24	0.21	0.20	0.18	0.25	0.53	0.87
t	-0.90	-3.06	-1.57	-1.22	0.13	0.72	1.25	-1.96	-2.56	-3.03
d.o.f.	51	65	65	63	64	64	63	57	54	48
t critical (ABS)	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.842
Difference α=0.05	s.d.	s.d.	s.d.	s.d.	n.s.d.	s.d.	s.d.	s.d.	s.d.	s.d.

Table D22: Initial site characterization - saturated soil paste extract EC (dS/m)

South	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75-90*	*105-120*	*135-150*	*165-180*
Mean	8.52	11.18	12.00	13.30	12.00	10.35	8.95	7.53	6.87	6.82
Standard Deviation	3.94	6.04	6.59	5.56	3.83	3.18	2.80	2.24	2.06	2.79
Minimum	1.86	1.03	1.23	1.60	1.33	3.42	3.59	4.30	3.36	3.13
Maximum	16.24	24.80	23.70	23.80	18.73	17.82	16.87	17.18	15.30	18.61
Count	34	39	39	37	39	39	38	34	33	31
CV (%)	46.22	54.02	54.92	41.83	31.95	30.70	31.30	29.67	29.91	40.91

North	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75-90*	*105-120*	*135-150*	*165-180*
Mean	6.75	11.26	13.33	13.43	11.93	10.40	8.75	7.39	6.24	4.51
Standard Deviation	3.26	4.47	5.13	4.57	3.73	3.34	2.90	2.67	2.17	2.60
Minimum	1.07	1.01	1.02	2.07	2.17	4.46	3.70	2.76	2.29	1.53
Maximum	12.93	18.32	19.58	19.50	17.60	16.41	15.10	12.47	9.75	10.78
Count	19	28	28	28	27	27	27	25	23	19
CV (%)	48.21	39.70	38.48	34.06	31.32	32.08	33.11	36.14	34.78	57.59

T-Test	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75-90*	*105-120*	*135-150*	*165-180*
s_p	3.71	5.44	6.03	5.16	3.79	3.24	2.84	2.43	2.10	2.72
t	1.66	-0.06	-0.89	-0.10	0.08	-0.06	0.29	0.22	1.10	2.91
d.o.f.	51	65	65	63	64	64	63	57	54	48
t critical (ABS)	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.842
Difference α=0.05	**s.d.**	**n.s.d.**	**s.d.**	**n.s.d.**	**n.s.d.**	**n.s.d.**	**n.s.d.**	**n.s.d.**	**s.d.**	**s.d.**

Table D23: Initial site characterization - saturated soil paste extract SAR.

South	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75-90*	*105-120*	*135-150*	*165-180*
Mean	16.41	19.07	18.53	18.82	18.27	18.22	18.11	18.77	17.22	16.19
Standard Deviation	15.07	15.61	14.77	12.78	9.61	10.19	11.58	15.55	12.12	15.91
Minimum	0.50	0.49	0.97	1.97	1.69	1.22	1.05	1.27	0.86	0.58
Maximum	63.94	66.77	63.25	58.94	43.73	44.25	47.65	76.78	43.02	58.82
Count	39	39	39	39	39	39	38	34	33	31
CV (%)	91.82	81.88	79.71	67.89	52.63	55.94	63.96	82.84	70.36	98.27

North	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75-90*	*105-120*	*135-150*	*165-180*
Mean	17.86	17.04	20.65	21.35	21.39	19.39	21.76	19.33	18.72	16.44
Standard Deviation	13.15	14.79	19.39	18.37	16.08	15.47	12.43	13.19	15.26	13.03
Minimum	0.40	0.42	0.36	0.57	0.75	0.91	1.42	1.02	0.75	0.64
Maximum	42.91	49.22	70.38	65.48	56.97	49.12	42.83	53.30	57.58	47.85
Count	28	28	28	28	28	27	27	25	23	19
CV (%)	73.62	86.77	93.87	86.06	75.17	79.78	57.14	68.24	81.53	79.24

T-Test	*0-10*	*10-20*	*20-30*	*30-45*	*45-60*	*60-75*	*75-90*	*105-120*	*135-150*	*165-180*
s_p	14.30	15.28	16.84	15.35	12.70	12.61	11.94	14.60	13.49	14.89
t	-0.41	0.54	-0.51	-0.67	-0.99	-0.37	-1.21	-0.14	-0.41	-0.06
d.o.f.	65	65	65	65	65	64	63	57	54	48
t critical (ABS)	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.648	0.842
Difference α=0.05	**n.s.d.**	**n.s.d.**	**n.s.d.**	**s.d.**	**s.d.**	**n.s.d.**	**s.d.**	**n.s.d.**	**n.s.d.**	**n.s.d.**

Table D24: Initial site characterization - saturated soil paste extract ionic concentrations (meq/l).

		Cl		SO4		Ca		Mg		Na		K	
	Depth (cm)	**mean**	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**
South parcel	*0-10*	1.6	1.7	144.7	128.2	18.3	8.2	43.5	42.0	106.6	114.3	1.3	1.3
	10-20	1.6	1.4	170.6	132.5	18.7	7.4	50.5	39.8	127.7	119.5	0.8	0.6
	20-30	1.3	1.3	165.6	133.5	17.8	7.6	52.8	43.7	123.8	120.7	0.6	0.3
	30-45	1.2	1.1	172.5	114.7	18.3	7.0	52.6	36.8	120.7	98.7	0.7	0.6
	45-60	1.2	1.4	161.1	90.6	18.6	6.6	48.3	32.7	107.3	66.7	1.1	1.1
	60-75	1.2	1.3	167.4	80.9	20.1	5.1	50.0	32.1	109.9	70.1	1.6	2.7
	75-90	1.2	1.3	168.2	97.4	20.0	5.9	53.4	36.2	116.0	91.3	1.1	1.5
	105-120	1.1	1.3	168.6	107.8	19.5	6.1	49.6	36.4	114.1	99.0	1.0	1.2
	135-150	1.4	1.7	154.7	98.9	19.6	5.8	47.9	36.7	107.7	89.5	1.6	2.1
	165-180	1.5	1.6	145.9	121.1	20.1	6.6	43.3	43.5	107.3	121.7	1.8	2.1

		Cl		SO4		Ca		Mg		Na		K	
	Depth (cm)	**mean**	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**
North parcel	*0-10*	2.0	2.6	110.7	83.5	17.3	8.4	32.0	26.0	97.5	90.9	1.7	3.1
	10-20	1.9	2.4	108.8	93.7	17.6	8.9	25.4	22.2	91.3	95.6	1.9	3.2
	20-30	2.0	3.1	136.5	138.9	15.3	8.9	30.6	31.8	117.2	130.6	1.1	1.9
	30-45	1.9	3.7	131.8	138.8	13.9	9.4	32.7	37.5	118.7	131.8	0.8	1.0
	45-60	2.1	3.3	145.8	121.7	16.6	8.0	35.3	34.4	123.3	121.9	1.7	3.1
	60-75	2.0	2.7	144.3	113.0	16.8	8.0	41.2	34.9	119.2	116.0	1.7	2.1
	75-90	2.1	2.7	161.4	96.5	19.1	6.8	39.2	24.3	124.4	87.9	1.4	2.0
	105-120	1.5	2.0	153.7	90.5	19.0	7.3	38.7	23.8	109.2	88.8	0.8	1.0
	135-150	1.7	2.4	130.9	95.0	16.7	8.0	35.1	25.3	101.9	97.3	0.8	0.8
	165-180	1.8	2.3	108.5	75.1	17.3	7.7	29.2	20.2	84.8	73.4	1.5	3.0

Table D25: Calculated porosity (%).

Depth (cm)	**South**	**North**
5	64	64
15	49	47
25	47	44
37.5	47	44
52.5	45	42
67.5	41	39
82.5	41	38
112.5	40	36
142.5	45	37
172.5	50	41

APPENDIX E: SOIL MOISTURE

Table E1: Average soil moisture measurements - south parcel.

Depth	8-May-98	5-Jun-98	8-Jul-98	17-Jul-98	12-Aug-98	26-Aug-98
5	8.0		8.2	4.2	3.6	3.5
15	23.6	21.3	27.5	25.1	22.1	21.1
25	28.7	29.1	31.8	31.6	28.5	28.0
35	30.2	30.6	32.2	32.9	29.9	29.7
45	31.2	31.5	32.8	33.7	30.6	30.3
55	31.9	31.7	32.1	33.8	30.9	30.5
65	32.4	32.4	32.5	32.9	31.8	31.4
75	32.6	32.7	32.6	33.2	32.0	31.6
85	32.7	32.3	32.5	33.3	31.6	31.7
95	32.8	32.6	32.7	33.3	31.9	31.7
105	33.0	33.0	32.9	33.0	32.4	32.2
115	33.8	33.6	33.2	33.4	32.9	32.6
125	34.8	34.8	34.4	35.9	34.1	33.7
135	35.9	36.5	36.5	36.2	35.9	35.5
145	37.1	37.9	37.3	37.7	36.6	36.4
155	38.5	39.6	38.5	40.2	37.7	37.6
165	39.8	40.8	39.9	41.7	39.6	38.8
175	40.6	41.5	40.6	42.5	40.9	40.1

Table E2: Average soil moisture measurements - north parcel.

Depth	8-May-98	5-Jun-98	8-Jul-98	17-Jul-98	12-Aug-98	26-Aug-98
5	17.6	9.1	19.3	10.6	8.5	6.0
15	30.7	29.6	33.5	29.4	26.4	23.9
25	32.0	33.3	34.7	33.1	30.2	28.5
35	32.9	34.1	34.8	33.1	29.8	28.7
45	33.7	34.0	35.0	33.3	29.6	28.7
55	34.2	34.7	35.3	33.8	30.6	29.4
65	34.9	35.1	35.6	34.3	31.7	30.7
75	34.9	35.1	35.3	34.3	32.3	31.1
85	34.8	34.8	34.8	33.6	31.9	31.0
95	34.3	35.1	34.6	33.5	32.1	31.0
105	33.9	35.4	34.8	33.9	32.0	31.1
115	33.8	35.2	34.5	33.4	31.9	31.2
125	33.8	35.1	34.0	33.7	32.2	31.7
135	35.0	35.1	34.2	33.9	31.9	31.9
145	34.9	35.6	33.1	33.3	32.6	31.7
155	35.0	36.0	34.3	33.4	33.2	32.9
165	35.0	36.3	35.2	33.9	33.9	33.1
175	36.5	37.5	37.5	36.1	36.4	35.6